# SCREENING HEART-SHAPED TOMATO CULTIVARS FOR YIELD AND QUALITY PERFORMANCE IN A SHORT GROWING SEASON

by

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## ABSTRACT

Tomatoes are among the most widely produced and consumed vegetable crops in the world. Even in challenging environments, their high value is an incentive for their production. In Montana, tomato production is challenged by a short and unpredictable growing season. Despite these challenges, most of Montana's vegetable growers produce tomatoes because of their high value and strong consumer demand. Locally produced and heirloom tomatoes can be marketed at a premium price due to their exceptional flavor and appearance; however, the climatic challenges faced by growers in Montana make selecting productive and flavorful cultivars difficult. To provide growers with data on the performance of specialty open-pollinated tomato cultivars under short-season conditions, this project evaluated 71 heart-shaped, open-pollinated tomato cultivars in a high tunnel under organic management. This class of cultivars showed potential adaptability to colder growing conditions and was evaluated over two growing seasons for yield, earliness, and fruit quality traits, including firmness, titratable acidity (TA), and soluble solids content (°Brix). The varieties 'Cuore di Toro,' 'Strawberry,' 'Reif Red Heart,' 'Korol Sibiri,' and 'Siberian Pink Honey' performed well with respect to both yield and quality traits in both years. Results from this trial will provide growers with data to support cultivar selection for flavorful and productive tomatoes within this market class.

# CHAPTER ONE

# EXPLORING HEART-SHAPED TOMATOES IN AN ORGANIC AND SHORT SEASON PRODUCTION SYSTEM: A LITERATURE REVIEW

## Introduction

Tomatoes are one of the most common vegetable crops in the world. In the U.S, the largest portion of vegetable production is dedicated to tomatoes (USDA, 2025). They are both a gardener and consumer favorite, prized for their unique flavors and colorful appearance and are popular in stores and farmer's markets throughout the country (Jordan, 2007).

The diversity of tomato varieties, both open-pollinated and F1 hybrid, is vast, reaching more than 10,000 varieties today (Benoit, 2023). Seed catalogs continue to introduce new tomato varieties to their inventory every year, which can make the selection of tomato varieties for production overwhelming for farmers and gardeners. Niche and heirloom varieties of tomatoes are valued and sought after for their taste, appearance, and fruit quality in local production systems (Jordan, 2007), but without the ability to screen this overwhelming variety of tomatoes, farmers might be disincentivized to look for more flavorful, attractive, and productive tomatoes for their customers and ones best suited to their climates. In Bozeman, MT, the short growing season and unpredictable frosts make local production of the cold-sensitive tomato quite challenging. The average frost-free growing season spans only about 100 days, but nevertheless consumer demand for tomatoes makes growing them quite lucrative for Montana's 400 or so vegetable growers.

The variety of tomatoes offered at American grocery stores for fresh consumption is quite narrow, featuring only handful of red slicers and several different cherry tomatoes. For decades consumers have been dissatisfied with the flavor of tomatoes offered in grocery stores, with modern commercial tomatoes not having the flavor of older, open-pollinated varieties (Bruhn et al., 1991; Malundo et al., 1995; Tieman et al., 2017). Several studies have revealed that tomatoes harvested green for a longer shelf-life make a great sacrifice to flavor because the sugar development is cut short in the fruit (Diehl et al., 2013; Klein et al., 2010; Resurreccion & Shewfelt, 2006). Local production makes it possible to have tomatoes that do not need a long shelf-life, having much more flavor potential and offering a summer delicacy for consumers. It is therefore important to find tomato varieties that are more adaptable to local conditions and could be both productive and uniquely flavorful in the local environment.

This recent demand for flavorful heirloom or heirloom-type tomatoes as a gourmet item has drawn interest from farmers as a high-value crop (Jordan, 2007). Formally, the term heirloom is a category of tomatoes that are open-pollinated and have existed as a cultivar for longer than 50 years. In recent years, “heirloom tomato” has been adopted as a marketing term to mean having an excellent flavor, a rustic-looking appearance, and local origins (Jordan, 2007). This demand can be used by local farmers to explore tomatoes with great flavor and unique appearance and stray from the traditional round, red tomatoes that consumers are used to in grocery stores.

In this study we screened open-pollinated, heart-shaped tomatoes with an indeterminate growth habit for high yield, earliness, fruit quality, and disease resistance under organic, covered culture. Many of these varieties fall into the oxheart morphological class and have the common characteristics of being very large, fleshy, with few seeds, and having fresh market eating flavor and texture. They have so few seeds that seed production can be quite difficult (Hudson Valley Seed Company, n.d.; TomatoFest, n.d.), but it makes them appealing for uses such as sandwiches and salsas where seeds are not desirable, but fleshiness is.

Many heart-shaped tomatoes and more specifically oxhearts have been bred in northern regions of Europe and have been quite popular there, particularly in Russia and Ukraine. These cultivars may be well adapted to colder climates and could produce well in Montana where there are about 100 frost free days compared to about 100 in Novosibirsk, RU and about 135 days in St. Petersburg, RU where some of the varieties in my project where released. In addition, the morphological class of 'heart-shaped' slicer tomatoes has not been widely explored through systematic research, which could help inform a wider audience about their characteristics and performance. They have the potential to fill a demand for unique and flavorful tomatoes for both local consumption and for local processing while providing breeding material for the development of new varieties. In my thesis, I screen heart-shaped, open-pollinated varieties for short-season suitability, fruit quality and productivity for local markets.

## Tomato Taxonomy

Tomatoes belong to the plant family Solanaceae with the center of diversity in South America where there is a great variety of wild species in the genus *Solanum* in the *Lycopersicon* group. *Lycopersicon* is a Greek word meaning "wolf peach" that was used for a different plant by a Greek naturalist many centuries prior to the arrival of the tomato to Europe and was later used by Linneus to classify all the cultivated multilocular forms of the tomato into one species: *Solanum lycopersicum* (Mattoo & Razdan, 2007). Of these, *S. lycopersicum* (common tomatoes) and *S. lycopersicum var. cersiforme* (cherry tomatoes) are the cultivated tomatoes that we now know and consume (Davies & Hobson, 1981).

## Cultivated Tomato History

The range of flavor and appearance of tomato plants and fruit comes from a long history of domestication, selection, and breeding efforts. Recent genetic research hypothesizes that the tomato was domesticated in two waves: first in northern Peru and Ecuador from the wild species *S. pimpinellifolium* to S. *lycopersicum* var. *cerasiforme* and another later in Central America from *S. lycopersicum* var. *cerasiforme* to *S. lycopersicum* var. *lycopersicum* (Monforte et al., 2014). The first wave of domestication happened when wind, people, and animals carried tomato seeds northward from the Andean region to Mesoamerica. At this time, there was likely a mutation that occurred in these plants that made the fruits larger and multi-locular. The second and more significant wave of domestication happened in Mexico under the Aztecs. The tomato was attractive to them as it was similar to the tomatillo, which was common in their diet, but was more disease resistant and had an attractive appearance (Hyman, 2019). The tomato was cultivated in traditional Aztec farming systems built over wetlands with tomatoes grown during the dry season. It was also grown as part of traditional milpa farming in the area (Saavedra et al., 2017).

The tomato plant was brought to Europe soon after Europeans arrived in the New World in the sixteenth century after a trading route out of the newly conquered Mexico was established. A Flemish herbalist Dodonaeus published a description of the tomato plant in his 1554 'Cruydeboeck' in which the plant can be clearly identified as the species (Jenkins, 1948). The Spanish had exposure to the tomato as a culinary vegetable, but it was not deemed commercially important and was seen with disdain (Hyman, 2019). Subsequently, the plant was thought by many to be poisonous and was primarily used as an ornamental or as a medicinal plant.

By the seventeenth century, the tomato's exotic New World origins made it a popular plant in elite gardens. In the first half of the seventeenth century in Spain, tomatoes began to appear in cookbooks and menus as well as being mentioned in poems and plays and portrayed in paintings. Starting from about this time, the use of the tomato as a culinary vegetable began to spread in parts of Europe (Hyman, 2019). It was only accepted as an edible fruit in Britain around 1850 (Jenkins, 1948). People began quickly inventing new recipes with tomatoes, including stuffed tomatoes, tomato sauce, sun-dried tomatoes and much, much more.

By the nineteenth century, tomatoes became quite common and abundant in Europe. A British gardener visiting Rome and Naples in the mid-nineteenth century noted that there were many fields dedicated to growing them and that there was hardly a dinner served without tomatoes featured on the menu (Hyman, 2019). Northern Europe was slower to adopting tomatoes, partially due to the shorter and less reliable growing seasons.

Meanwhile in Mexico where the tomato was discovered by Europeans, a series of disruptions changed the way that tomatoes were cultivated. Drainage of lake Texcoco by the Spanish and a series huge epidemics both changed the farming environment and the knowledge of traditional systems (Saavedra et al., 2017). Although the Spanish adopted many Aztec tomato recipes, after the changes in agriculture and environment in Mexico, European methods for cultivating tomatoes began to dominate (Saavedra et al., 2017)

In the American colonies and then in the United States, the adoption of tomatoes was also slow. Initially, there was concern that they were poisonous as well as suspicion towards many raw vegetables generally due to the risk of disease (Hyman, 2019). There are many legends about how tomatoes as edible, culinary vegetables were introduced to the United States. The first known reference to tomatoes in the area that later became the U.S. came from an English botanist William Salmon around 1690 when he wrote about seeing them in Carolina. (Smith, 1994). His reference led to several theories of their appearance there. One possibility is that they spread from the Spanish settlements in Florida where they were likely cultivated and consumed earlier in the seventeenth century. Another possibility is that French Huguenot refugees or British colonists brought seeds from Europe to the American colonies. Yet another theory is that tomatoes may have been introduced from the Caribbean where migrations and extensive trade with the American colonies started in the late seventeenth century continuing through the eighteenth century (Smith, 1994).

During the eighteenth century, tomatoes were cultivated more extensively in Georgia as well as in the Carolinas. In the latter part of that century, they started to spread northward and into the interior of the country as colonization moved up the Mississippi and westward. At this time there is also an increase in the culinary literature that suggests that tomatoes were extensively consumed and integrated into local cuisines (Hyman, 2019). The variety of uses for tomatoes in the United States increased as well, including tomato processing and canning during the height of the tomato season. Novel processing recipes such as tomato ketchup also appeared during this time (Smith, 1994).

In the aftermath of the Civil War, tomato cultivation, consumption, and processing expanded quickly. Feeding soldiers canned goods and particularly food with tomatoes was lucrative and popular, leading to an explosion in acreage dedicated to tomatoes and factories for canning tomatoes. As the industry grew, the government raised tariffs on imported vegetables and subsequently the Supreme Court famously ruled that tomatoes are to be considered a vegetable in the case Nix v. Hedden in 1893 (Hyman, 2019).

As commercial production grew, breeding tomatoes did as well. Alexander Livingston, an Ohio tomato breeder in the late 1800s became a pivotal figure in developing commercial tomato varieties through single plant selection to fulfill the demands of the market (Smith, 1994). Around the same time, Liberty Hyde Bailey, an agricultural researcher, began testing varieties sold by seedsmen. His work was prompted by several factors: the influx of new American tomato varieties, the reluctance of seedsmen to remove name duplicates, the tendency to list varieties as distinct that didn’t differ much from others, and the introduction of renamed European varieties (Smith, 1994). These issues still persist to an extent as many open-pollinated varieties have a blurry history and come from a variety of disconnected sources.

Many older heirloom varieties became less popular as hybrid tomatoes started to dominate the commercial market in the first half of the twentieth century. Tomato hybridization research expanded and commercialized after Richard Wellington’s work in 1912 in Geneva, New York (Wellington, 1912). Hybrid tomatoes are the progeny of a specific parental cross. Hybridizing tomatoes creates a cultivar that is often more vigorous and uniform than an inbred cultivar but requires growers to buy pricier seeds from a seed company every season. This poses an important question of farmers’ autonomy and food sovereignty when growers cannot save their own seeds and instead rely on buying seeds each year. In contrast to hybrids, open-pollinated varieties are often prized for their flavor (Jordan, 2007). There is potentially a fruit quality and flavor advantage in open-pollinated varieties because of the additive gene action of the many genes controlling fruit quality (Avdikos et al., 2021). As a result, tomatoes that are homozygous for these genes will have higher fruit quality than hybrids. This could be a reason that heirloom tomatoes are considered to have superior flavor, but it is possible that the breeding goals for commercial hybrid varieties didn't focus on flavor and led less flavorful varieties.

In recent years there has been a revival in interest and demand for open-pollinated varieties, with efforts to bring back forgotten varieties and to preserve the diversity of available heirlooms. An organization that contributes to these efforts in the United States is the Seed Saver's Exchange (SSE) which was established in 1975. Their goal is to connect people with open-pollinated seeds, to revitalize some of these varieties, and to have them grown. Currently, seed-saving of open-pollinated varieties happens at the SSE and both provides growers with unique varieties and breeding material for breeders. While I am mainly focusing on regional adaptability of the heart-shaped class of open-pollinated varieties, another goal of this thesis is to collect more information on unique varieties and to provide this information to breeders and farmers.

## Heart-shaped Tomato History

Many of the varieties tested in this trial are varieties that were selected in various parts of Europe and Asia before being imported to the U.S. Heart-shaped tomatoes in this study are categorized as common sized tomatoes that are morphologically heart-shaped with a pointed tip at the blossom end and lofty shoulders. When exploring the history of heart-shaped tomato varieties, we must turn back to when tomatoes began to spread throughout Europe after their cultivation and consumption became accepted. Heart-shaped varieties began to appear in various parts of Europe, but many within this class were developed in Italy and then in various parts of Eastern Europe.

The tomato came to the Russian Empire from Europe in the 1780s (Brezhnev, 1955). Similarly to early European encounters with the plant, in Russia it was mainly a decorative plant that was not used for consumption and instead mentioned in herbalist catalogs and sometimes mentioned to be edible. By the 1850s, the fruit started to be produced at larger scales for consumption. Local breeding of tomatoes began afterward with many new varieties coming forth (Brezhnev, 1955).

In the article called, “The Tomato in Northern Horticultural Regions” from the journal *The Agricultural Library 1916*, M.V. Rytov writes that many oblong, heart-shaped, and meaty tomato varieties were developed from foreign tomato varieties in northern regions of the Russian Empire and were considered to be hardier than imported varieties. These varieties were developed privately by farmers, gardeners, and tomato hobbyists. Due to the lack of documentation and research, the history of the breeding of those tomatoes is unclear. Rytov also attributes this lack of documentation to lack of an agricultural research station in the St. Petersburg area, where he was conducting his study (Rytov, 1916). As seen in both Rytov and Brezhnev’s work, many oxheart tomato types were never bred for commercial production and instead used and bred by gardeners. These locally-bred tomatoes couldn’t be classified as a unique cultivar since their origin and uniqueness were not documented (Rytov, 1916). By the time that Soviet agricultural research stations began broader research into indeterminate tomatoes for commercial greenhouse production, hybrids became much more popular and widespread (Brezhnev, 1955). Nevertheless, some oxheart varieties continued to be sought after by gardeners and small-scale growers with the varieties improved by local institutes. One such example is the cultivar 'Bull's Heart' which was developed by Vavilov's Institute of Plant Industry.

The above history does not apply to all varieties tested in this trial, but it does illustrate the story behind some of the varieties such as 'Bull's Heart,' 'Anna Russian,' 'Oxheart,' 'Russian 117,' 'Korol Sibiri,' and others. There are a number of cultivars in this trial that did not come from Italy or Eastern Europe to the U.S, but the stories of these tomatoes are difficult to track.

Several heart-shaped tomato varieties that are now available in the U.S were brought by immigrants from various parts of Europe and eventually were given to seed companies. The Seed Saver's Exchange, which has procured a variety of open-pollinated tomatoes often gets information about a cultivar's history and origins from its donors. Craig LeHoullier and Sara Straate of Seed Savers Exchange say that beyond the information that donors provide on varieties, there is little known about the history of many heart-shaped varieties (Craig LeHouillier, Sara Straate, personal communication, November 2024). Much like many open-pollinated tomato varieties, their breeding history remains shrouded in mystery. Nevertheless, the information found on heart-shaped tomatoes and their successful breeding and selection in the Russian Empire serves as a pointer to their potential in colder regions of the U.S.

## Tomato Market Classes

Tomato market classes are determined by size and shape parameters as well as fruit quality and growth habit. There are two growth habits within cultivated tomato varieties: determinate and indeterminate. Determinate tomatoes are bred to have a low or bush growing habit and to flower within a short window so that the fruit all matures at the same time and can be harvested at once. Indeterminate tomatoes have an upright vine that requires trellising and adapts them to a trellis system or to greenhouse or high tunnel production. They flower and produce fruit throughout the growing season. Within these two classes, there are generally two categories based on size: cherry and common tomato. Some sources also add a third category of cylindrical tomatoes and then further divide the above three categories by size: small, medium, and large (Behera et al., 2019). There is some additional nuance within these categories, but generally most varieties fall into one of them. Market demand also drives the subdivision of the main categories of cherry, classical, and cylindrical tomatoes into more specific categories. These categories are based on purpose and include processing tomatoes, fresh market tomatoes, heirloom tomatoes, salad and slicing tomatoes and more.

Tomatoes can also be categorized based on shape. Tomatoes are typically put into 8 shape categories: flat, rectangular, ellipsoid, obovoid, round, oxheart, long, and heart (Monforte et al., 2014; Rodríguez et al., 2011). Although certain fruit qualities are not intrinsically connected to shape, certain classes of tomatoes have similar shape characteristics along with certain flavor and texture characteristics. For example, flat and large beefsteak tomatoes are prized for their meaty and fleshy texture, but do not necessarily have the best flavor. Similarly, tomatoes meant for sauce or other processing are typically oblong and midsized and are higher than others in dry matter (Hyman, 2019). Fresh market tomatoes are typically eaten raw and therefore have a focus on flavor, appearance, and a texture that satisfies the consumer.

Tomato colors also vary significantly, the most common being yellow, orange, purple, red, pink, green, marbled, and striped. Tomatoes used for processing are almost always bright red in color, while ones meant for fresh market offer a diversity of colors to attract consumers.

Heart-shaped tomatoes are typically medium, large or very large tomatoes. They are commonly fleshy, but not quite dry enough to be categorized as processing tomatoes. They come in many different colors, some of which are red, pink, blue, yellow, orange, and striped. Their shape sets them aside from others with their lofty and smooth shoulders and a pronounced tear-drop shape towards the blossom end.

## Genetics of the Heart Shape

The variation in tomato fruit shape has a genetic basis and was the result of mutation and human selection of specific phenotypes. After the domestication of the tomato, the morphology of the fruit changed and diversified. The most drastic of these changes were in fruit size, shape, and locule number. The shape of tomato fruit is mostly controlled by variation in four main genes. These genes are FAS, SUN, LC, and OVATE (Rodríguez et al., 2011). The mutations in genes FAS, SUN, and LC appear to have occurred pre-domestication or in the early process of domestication within the same ancestral population, while the mutation in the gene OVATE arose much later in Europe (Rodríguez et al., 2011).

These genes control both fruit size and shape before and after anthesis by controlling organ patterning and the rate and plane of cell division in the fruit (Monforte et al., 2014). The SUN and OVATE genes control fruit elongation while LC and FAS regulate locule number and flat or oxheart fruit shape respectively. The gene SUN controls tomato shape through increased cell division in the longitudinal direction and decreased cell division in the transverse direction of the fruit (Wu et al., 2011).

Large heart-shaped tomatoes have been labelled in different ways that all describe the same shape category. They have been described as having cordate, heart-shaped, and oxheart shape (IPGRI, 1996; Rodríguez et al., 2011; UPOV, 2024). All of these describe the same shape category: large tomatoes of a classic heart shape with a distinctive blossom-end tip. According to a study done by Rodríguez in 2011 on 368 tomato accessions, 83% of the oxheart type tomatoes had the mutant allele of the SUN gene. All of the tomatoes within this shape category carried the LC mutation as well as the FAS and/or the SUN mutation (Rodríguez et al., 2011). Heart-shaped tomatoes have a mutation for a greater number of locules and another one or two mutations that gives them their signature heart shape with an elongated tip and wide shoulders.

## Consumer Preferences

Tomatoes available in mainstream grocery stores typically lack satisfactory flavor and texture characteristics. There have been a number of studies noting consumer dissatisfaction prominently starting in the 90s (Baldwin et al., 1998; Bruhn et al., 1991; Malundo et al., 1995; Tieman et al., 2017). A study based in California found that consumer satisfaction was especially low with tomatoes and apricots (Bruhn et al., 1991). These complaints could be addressed by harvesting a more mature product and therefore having a more developed flavor and a better texture because tomatoes harvested at the breaker stage and then ripened in storage have inferior flavor development (Kader et al., 1977). The dissatisfaction with commercial tomato flavor may also stem from flavor not being the central focus of developing these tomato varieties. The goals of modern commercial tomato breeding prioritize yield and preservation of vigor and prevention of decreased yields in varieties (Tieman et al., 2017). In addition to this, when wild tomato genetics have been introduced in the breeding process to continue yield gains, they often carry linkage drag that has an effect on the flavor and metabolome of commercial tomato varieties (Zhu et al., 2018).

Apart from flavor, another aspect that affects consumer perceptions of tomatoes is the external characteristics of the fruit such as the color, shape, and size (Klein et al., 2010). It is possible that consumers' perception of flavor of tomato varieties might be influenced by their specialty colors, sizes, and shapes making sensory evaluation poorly related to aroma compound profiles and to sugar and acid levels (Klein et al., 2010). Fruit appearance and price point are characteristics that influence consumer preferences. A recent literature review described that consumers prefer intensely red fruit with an even color (Latino et al., 2023). There was some disagreement on preference of fruit firmness, but most studies showed that people gravitate towards fruit that looks most fresh and has least external damage. For flavor preference, rather than finding agreement in consumer preference, there were clusters of preferences where certain groups of people preferred different traits. Some of these were sweetness, acidity, seed presence, juiciness, aroma, and consistency (Latino et al., 2023).

Aroma compounds such as geraniol can enhance the perception of sweetness and flavor in tomatoes without increases in sugars. Although research has looked at various volatile compounds present in tomato varieties, it is usually the less abundant compounds that make a greater contribution to taste perceptions rather than the ones that are more abundant (Tieman et al., 2012). Being able to predict consumer response to a certain tomato is key to both testing varieties and for breeding ones with better flavor, confirmed by a chemic analysis combined with a correlation with human sensory analysis More recently, new approaches have been used to tackle the expanding demand for flavorful tomatoes. This has included genetic analysis of fruit flavor and machine learning approaches (Wang et al., 2022). The dissatisfaction with tomato flavor has led to both the popularity of heirloom tomatoes with consumers as well as increased breeding efforts to improve flavor in conventional commercial tomato production (Jordan, 2007; Tieman et al., 2017). Although locally produced tomatoes are grown for attractive flavor and appearance, they are a seasonal delicacy that cannot replace larger commercial tomato production that makes tomatoes available year-round. Nevertheless, these tomatoes have a high value to consumers and will continue to be a sought-after product. Fruit quality analysis of heart-shaped varieties will help bring out the genotypes that have superior flavor, texture, and appearance both for consumer satisfaction and for future breeding efforts.

## Chemical and Sensory Analysis of Tomato Flavor

Flavor is arguably the most important tomato fruit quality characteristic. Tomato varieties are prized for their unique flavor and although there is nuance in personal preferences for particular aspects of flavor, there are generally accepted flavor quality parameters. Focusing on flavor for variety trialing and breeding is always important, but particularly critical today since, as mentioned earlier, breeding has been focused on maximizing yield, contributing to flavor quality erosion and consumer's persisting dissatisfaction with tomato flavor (Bruhn et al., 1991; Zhu et al., 2018).

Tomato flavor is characterized by several main components that include acid content, sugar content, and volatile compounds. These can vary significantly between varieties and effect acceptability and preference. Levels of sugar and acid are vital to consumer acceptability with increased sugar levels and increased acid levels up to a certain point positively correlated with improved flavor. In a study by (Malundo et al., 1995), the results indicated that increasing acid levels beyond a pH of 3.74 or 0.80% citric acid as determined by titratable acidity, reduces flavor acceptability at any given sugar level. This shows that there is a level of acidity in a tomato beyond which increased acidity reduces flavor quality. This study also confirms earlier studies that suggest that a sugar to acid ratio or sugar to titratable acidity ratio does not work as a good indicator for tomato flavor (Malundo et al., 1995; Resurreccion & Shewfelt, 2006; Stevens et al., 1979). These studies show that defining tomato flavor to specific values is not realistic, but higher levels of sugars and higher levels of acidity improve flavor up to a maximum amount of acidity.

Both chemical and sensory analysis is necessary to determine whether selection for improved taste could be carried out (De Bruyn et al., 1971). Chemical analysis is typically done by using a refractometer or HPLC machine to determine sugar levels that is read as a measure of °Brix, a pH probe or acid titrations for determining acidity, and gas chromatography to assess volatile compound content. A study in 1971 found that genotypes did have significant differences in taste, but chemical analysis cannot entirely replace sensory analysis for the purpose of selection. As a result, both chemical and sensory analyses need to be conducted in order to select for improved taste in tomatoes. Another reason for this is the variability of acid and sugar within parts of a tomato fruit making it challenging to accurately test tomato flavor through chemical analysis. The flesh of the tomato is higher in sugar and lower in acid while the locules and its contents are higher in acid and lower in sugar (De Bruyn et al., 1971). This observation would imply that fleshy tomatoes with small locules like heart-shaped varieties would have a lower acidity level overall and potentially higher levels of sugar compared to varieties with larger proportion of locule space.

In 2003, a study with the objective of linking sensory descriptors to both volatile and non-volatile components of flavor was conducted. The study showed that sucrose equivalents had a stronger correlation to sweetness than soluble solids (Tandon et al., 2003), confirming that a tomato that is described as “full-flavored” was higher in sugars and aromatic volatile compounds and lower in acids than tomatoes that were described as “poor-flavored” (Baldwin et al., 1998). Further, higher dry matter content correlates with sugar content in tomatoes and tomatoes with a yellow or blue hued skin correlates with higher sugar and citric acid content (Andelini et al., 2023). Andelini found that the most important parameters discriminating their landrace varieties were dry matter, malic acid, citric acid, and fructooligosaccharide content.

Although aromatic compounds play a part in characterizing tomato flavor, it is the sugars, soluble solids and titratable acidity that correlate strongly with overall taste of a tomato (Baldwin et al., 1998). Nevertheless, Baldwin’s study showed that overall levels of aroma compounds affected perceptions of sweetness and sourness by the tasting panel. Research regarding the quantification and analysis of tomato flavor continues to develop. The flavor of a tomato is important to consumers, but the yield of a tomato cultivar will continue to be the anchoring characteristic for grower’s choices of varieties.

## Short Season Tomato Production

In areas where tomato yield is impacted by temperature or shortness of the growing season, growing tomatoes under plastic has become quite popular. Using high tunnels, hoop houses, and greenhouses has helped growers extend the season for warm-season crops such as tomatoes. Using a covered structure is especially vital in places that have shorter or otherwise compromised growing seasons. Numbers of studies have been done showing the yield advantage or increased marketability of tomatoes in these structures, especially in colder regions (Healy et al., 2017; O’Connell et al., 2012; Rogers & Wszelaki, 2012). Farmers and researchers have both experimented with additional protection of these crops. Organic cherry tomato yield has been shown to be greater in a high tunnel compared to the open field (Kong et al., 2020). The outcome of this study showed that high tunnel and high tunnel with insect netting protection gave higher marketable tomato yield and less disease and pest damage, but tomatoes yielded consistently higher in a high tunnel than tomatoes in a high tunnel with insect netting.

Further, research has been done on the effect of sub-optimal temperatures on tomato growth and yield. A summary of the literature reveals that sub-optimal temperatures result in larger plants with thicker leaves and fewer fruit (Van Ploeg & Heuvelink, 2005). The growth rate of these plants slows down and fruit set decreases because of lower pollen quality. The time between anthesis and mature fruit is longer because of the slower growth rate. Plants at higher-than-optimal temperatures produce mature fruit faster, but this happens at the cost of vegetative growth and later trusses (Van Ploeg & Heuvelink, 2005). These patterns can be observed in short season in an unheated greenhouse when growth is slow at the beginning of the season and ripening occurs slowly as well, but as the temperatures rise, fruit maturation and growth rate quicken.

Although production of tomatoes in unheated and covered structures has become very popular among growers in colder regions, knowledge of cultivars that are better suited for this system has not been thoroughly explored. However, there is demand for locally grown, specialized tomatoes with consumers, and improvements to an organic and protected tomato system would be greeted well both by consumers and growers.

The tomatoes used in this trial were grown in an unheated high tunnel under organic management since it is a common practice for tomato growers in Montana to use these methods to enhance the value of their product.

## Organic and Hoophouse Tomato Production

Organic products are certified by the USDA through the organic certification process. This process has specific standards that can help consumers decipher the means by which a product has been produced. For farm produce, farmers are restricted from using synthetic fertilizers, sewage sludge, irradiation, and genetic engineering. Other substances such as synthetic pesticides and herbicides also cannot be used (McEvoy, 2016).

In 2011, 95% of organic production overall was based on crop varieties bred for conventional, high input systems (Lammerts van Bueren et al., 2011). Some of the key challenges in organic production that could be addressed with specific breeding efforts include nutrient use efficiency, weed competition, tolerance to mechanical weed control, resistance to seed-borne diseases, insects, fungal and bacterial diseases, and tolerance to abiotic stress. Through variety trials, crosses, and selection, new varieties that are more suited for organic production can continue to be produced.

In 2023, Romdhane et al. successfully tested a tomato germplasm line OSTGL for its performance in an organic system compared to another popular cultivar in organic production. The OSTGL line produced higher marketable yield and had comparable values for weight, soluble solids, pH, titratable acidity, firmness and coloration, lycopene and beta-carotene contents demonstrating the importance of breeding under organic systems (Romdhane et al., 2023).

The performance of different tomato varieties under varied organic conditions is also important for finding varieties that are better suited to those conditions. In Montana and throughout the U.S., tomatoes in organic systems are commonly produced under a plastic cover whether this is in a greenhouse, hoophouse, caterpillar tunnel or other structure. In a study by Rogers and Wszelaki (2012), both hybrid and heirloom tomato varieties were grown in high tunnels and in the field under organic conditions. Hybrid varieties yielded more than heirloom varieties, but the authors suggest that because heirloom tomatoes have a higher market value for growers, the adjusted value of hybrids and heirlooms would be the same even with lower yields of heirlooms (Rogers & Wszelaki, 2012). Both this study and a study by O'Connell (2012) showed that yields inside a hoop house and field don't typically differ, although in one year of O'Connell's study tomatoes in the hoop house did significantly outyield the field (O'Connell et al., 2012). These studies were done in Tennessee and North Carolina respectively and may not be relevant to colder regions. Nevertheless, these studies did establish that tomatoes grown in a hoop house are less prone to diseases and deformity and yielded more marketable fruit. In a more northern region, these benefits could be amplified by the temperature advantage of hoophouses when days are cooler.

Another study sums up yield and quality characteristic outcomes in the field versus in a greenhouse under organic conditions (Healy et al., 2017). In this study, 19 cultivars were compared between hoophouse and field management for yield and quality parameters important to organic tomato growers in Wisconsin. The study found that the hoophouse tomatoes had higher °Brix and yield and lower disease severity than plants grown in the field. The differences in these characteristics were greater between management systems than between varieties. This outcome leads to the clear conclusion that growers will benefit from growing tomatoes in hoophouses regardless of cultivar. Therefore, further research into varieties that perform well under organic hoophouse production will lead to more effective production of these tomatoes as well as more material for breeders who seek to improve tomatoes grown in these conditions.

## Conclusion

Tomatoes are one of the most commonly consumed vegetables in the U.S (USDA, 2020). Not all regions of this country have an optimum environment for tomato growth, but the adaptability and performance of tomatoes in different environments varies greatly between varieties. Montana's challenges in tomato production don't stop growers from choosing this sensitive crop due to its popularity with consumers, but they do make choosing varieties quite difficult. It is often hard to predict how a cultivar might perform or ripen in this area when varieties are tested in very different conditions. The heart-shaped tomatoes in this trial were screened using methods emulating the common practices of vegetable growers in the region, using high tunnels and organic practices for production. These varieties have the potential to provide good yields and unique flavor and quality characteristics that might make them attractive to Montana tomato growers.

## References

Andelini, M., Major, N., Išić, N., Kovačević, T., Ban, D., Palcic, I., Radunic, M., & Goreta Ban, S. (2023). Sugar and Organic Acid Content Is Dependent on Tomato (Solanum Lycoperiscum L.) Peel Color. *Horticulturae*, *9*, 313. https://doi.org/10.3390/horticulturae9030313

Avdikos, I. D., Tagiakas, R., Tsouvaltzis, P., Mylonas, I., Xynias, I. N., & Mavromatis, A. G. (2021). Comparative evaluation of tomato hybrids and inbred lines for fruit quality traits. *Agronomy*, *11*(3), 609. https://www.mdpi.com/2073-4395/11/3/609

Baldwin, E. A., Scott, J. W., Einstein, M. A., Malundo, T. M. M., Carr, B. T., Shewfelt, R. L., & Tandon, K. S. (1998). Relationship between sensory and instrumental analysis for tomato flavor. *Journal of the American Society for Horticultural Science*, *123*(5), 906-915. https://doi.org/10.21273/jashs.123.5.906

Behera, S., Mahapatra, A., Rath, A., & Sethy, P. (2019). Classification & grading of tomatoes using image processing techniques.

Benoit, D. J. (2023, February 8). *A history of tomatoes*. University of Vermont Extension. A history of tomatoes

Brezhnev, D. D. (1955). *Томаты [Tomatoes]* (L. a. Brozheyt, Ed.). The State Publishing of Agricultural Literature.

Bruhn, C. M., Feldman, N., Garlitz, C., Harwood, J., Ivans, E., Marshall, M., Riley, A., Thurber, D., & Williamson, E. (1991). Consumer perceptions of quality: apricots, cantaloupes, peaches, pears, strawberries, and tomatoes. *Journal of Food Quality*, *14*(3), 187-195. https://doi.org/https://doi.org/10.1111/j.1745-4557.1991.tb00060.x

Davies, J. N. and G. E. Hobson (1981). "The constituents of tomato fruit: the influence of environment, nutrition, and genotype." CRC critical reviews in food science and nutrition **15**(3): 205-280.

De Bruyn, J. W., Garretsen, F., & Kooistra, E. (1971). Variation in taste and chemical composition of the tomato (Lycopersicon esculentum Mill.). *Euphytica*, *20*(2), 214-227. https://doi.org/10.1007/BF00056081

Diehl, D., et al. (2013). "Exploring produce industry attitudes: Relationships between postharvest handling, fruit flavor, and consumer purchasing." HortTechnology **23**: 642-650.

Healy, G. K., Emerson, B. J., & Dawson, J. C. (2017). Tomato variety trials for productivity and quality in organic hoop house versus open field management. *Renewable agriculture and food systems*, *32*(6), 562-572. https://doi.org/10.1017/S174217051600048X

Hudson Valley Seed Company. (n.d.). *Upstate Oxheart tomato*. https://hudsonvalleyseed.com/products/upstate-oxheart-tomato

Hyman, C. (2019). *Tomato : A Global History*. Reaktion Books, Limited. http://ebookcentral.proquest.com/lib/montana/detail.action?docID=5839385

IPGRI. (1996). *Descriptors for Tomato (Lycopersicon spp.)*.

Jenkins, J. A. (1948). "The Origin of the Cultivated Tomato." Economic botany **2**(4): 379-392.

Jordan, J. (2007). The heirloom tomato as cultural object: investigating taste and space. *Sociologia Ruralis*, *47*, 20-41. https://doi.org/10.1111/j.1467-9523.2007.00424.x

Kader, A. A., Stevens, M. A., Albright-Holton, M., Morris, L. L., & Algazi, M. (1977). Effect of Fruit Ripeness when Picked on Flavor and Composition in Fresh Market Tomatoes1. *Journal of the American Society for Horticultural Science*, *102*(6), 724-731. https://doi.org/10.21273/jashs.102.6.724

Klein, D., Gkisakis, V., Krumbein, A., Livieratos, I., & Köpke, U. (2010). Old and endangered tomato cultivars under organic greenhouse production: effect of harvest time on flavour profile and consumer acceptance. *International Journal of Food Science & Technology*, *45*(11), 2250-2257. https://doi.org/https://doi.org/10.1111/j.1365-2621.2010.02398.x

Kong, Y., Llewellyn, D., & Zheng, Y. (2020). High tunnels without anti-insect netting benefit organic cherry tomato production in regions with cool and short growing seasons. *Canadian journal of plant science*, *100*(4), 401-414. https://doi.org/10.1139/cjps-2019-0243

Lammerts van Bueren, E. T., Jones, S. S., Tamm, L., Murphy, K. M., Myers, J. R., Leifert, C., & Messmer, M. M. (2011). The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: A review. *NJAS - Wageningen journal of life sciences*, *58*(3), 193-205. https://doi.org/10.1016/j.njas.2010.04.001

Latino, M. E., Menegoli, M., & Corallo, A. (2023). Relevant attributes influencing consumers' tomato acceptance: A systematic review and research agenda. *Journal of agricultural & food industrial organization*, *21*(2), 129-146. https://doi.org/10.1515/jafio-2021-0047

Malundo, T. M. M., Shewfelt, R. L., & Scott, J. W. (1995). Flavor quality of fresh tomato (Lycopersicon esculentum Mill.) as affected by sugar and acid levels. *Postharvest Biology and Technology*, *6*, 103-110.

Mattoo, A., & Razdan, M. K. (2007). *Genetic improvement of solanaceous crops. Volume 2, Tomato* (1st ed.). Science Publishers. https://doi.org/10.1201/b10744

McEvoy, M. (2016). *Understanding the USDA Organic Label*. USDA.

Monforte, A. J., Diaz, A., Caño-Delgado, A., & van der Knaap, E. (2014). The genetic basis of fruit morphology in horticultural crops: lessons from tomato and melon. *Journal of experimental botany.*, *65*(16), 4625-4637. https://doi.org/10.1093/jxb/eru017

O'Connell, S., Rivard, C., Peet, M. M., Harlow, C., & Louws, F. (2012). High tunnel and field production of organic heirloom tomatoes: Yield, fruit quality, disease, and microclimate. *HortScience horts*, *47*(9), 1283-1290. https://doi.org/10.21273/hortsci.47.9.1283

Resurreccion, A. V. A., & Shewfelt, R. (2006). Relationships between sensory attributes and objective measurements of postharvest quality of tomatoes. *Journal of food science*, *50*, 1242-1245. https://doi.org/10.1111/j.1365-2621.1985.tb10452.x

Rodríguez, G. R., Muños, S., Anderson, C., Sim, S.-C., Michel, A., Causse, M., Gardener, B. B. M., Francis, D., & van der Knaap, E. (2011). Distribution of SUN, OVATE, LC , and FAS in the tomato germplasm and the relationship to fruit shape diversity. *Plant physiology.*, *156*(1), 275-285. https://doi.org/10.1104/pp.110.167577

Rogers, M. A., & Wszelaki, A. L. (2012). Influence of high tunnel Production and planting date on yield, growth, and early blight development on organically grown heirloom and hybrid tomato. *HortTechnology (Alexandria, Va.)*, *22*(4), 452-462. https://doi.org/10.21273/HORTTECH.22.4.452

Romdhane, A., Riahi, A., Piro, G., Lenucci, M. S., & Hdider, C. (2023). Agronomic performance and nutraceutical quality of a tomato germplasm line selected under organic production system. *Horticulturae*, *9*(4), 490. https://doi.org/10.3390/horticulturae9040490

Rytov, M. V. (1916). Томат в Северной Полосе Огородничества [The Tomato in Northern Horticultural Regions]. *The Agricultural Library*, 36.

Saavedra, T. M., Figueroa, G. A., & Cauih, J. G. D. (2017). Origin and evolution of tomato production Lycopersicon esculentum in México. *Ciência rural : revista científica do Centro de Ciências Rurais da Universidade Federal de Santa Maria.*, *47*(3), 20160526. https://doi.org/10.1590/0103-8478cr20160526

Smith, A. F. (1994). The Tomato in America: Early History, Culture, and Cookery. Columbia, South Caroline, University of South Carolina Press.

Stevens, M., Kader, A., & Albright, M. (1979). Potential for increasing tomato flavor via increased sugar and acid content. *J. Amer. Soc. Hort. Sci.*, *104*, 40-42. https://doi.org/10.21273/JASHS.104.1.40

Tandon, K. S., Baldwin, E. A., Scott, J. W., & Shewfelt, R. L. (2003). Linking sensory descriptors to volatile and nonvolatile components of fresh tomato flavor. *Journal of food science*, *68*(7), 2366-2371. https://doi.org/10.1111/j.1365-2621.2003.tb05774.x

Tieman, D., Bliss, P., McIntyre, Lauren M., Blandon-Ubeda, A., Bies, D., Odabasi, Asli Z., Rodríguez, Gustavo R., van der Knaap, E., Taylor, Mark G., Goulet, C., Mageroy, Melissa H., Snyder, Derek J., Colquhoun, T., Moskowitz, H., Clark, David G., Sims, C., Bartoshuk, L., & Klee, Harry J. (2012). The chemical interactions underlying tomato flavor preferences. *Current Biology*, *22*(11), 1035-1039. https://doi.org/10.1016/j.cub.2012.04.016

TomatoFest. (n.d.). *Heart shaped tomatoes*. https://www.tomatofest.com/Heart_Shaped_Tomatoes_s/64.htm

UPOV. (2024). Guidelines for the conduct of tests for distinctiveness, uniformity and stability (tomato). *UPOV, Geneva*, p.17-35.

USDA. (2020). *Potatoes and tomaotes are the most commonly consumed vegetables*. USDA. https://www.ers.usda.gov/data-products/chart-gallery/chart-detail?chartId=58340

USDA. (2025). *Vegetables 2024 Summary*. (0884-6413). USDA

Van Ploeg, D., & Heuvelink, E. (2005). Influence of sub-optimal temperature on tomato growth and yield: a review. *The Journal of Horticultural Science and Biotechnology*, *80*(6), 652-659. https://doi.org/10.1080/14620316.2005.11511994

Wang, S., Qiang, Q., Xiang, L., Fernie, A. R., & Yang, J. (2022). Targeted approaches to improve tomato fruit taste. *Horticulture Research*, *10*(1). https://doi.org/10.1093/hr/uhac229

Wellington, R. (1912). Influence of crossing in increasing the yield of tomato. *Bulletin by New York Agricultural Experiment Station*(No. 346).

Wu, S., Xiao, H., Cabrera, A., Meulia, T., & Knaap, E. (2011). SUN regulates vegetative and reproductive organ shape by changing cell division patterns. *Plant physiology*, *157*, 1175-1186. https://doi.org/10.1104/pp.111.181065

Zhu, G., Wang, S., Huang, Z., Zhang, S., Liao, Q., Zhang, C., Lin, T., Qin, M., Peng, M., Yang, C., Cao, X., Han, X., Wang, X., van der Knaap, E., Zhang, Z., Cui, X., Klee, H., Fernie, A. R., Luo, J., & Huang, S. (2018). Rewiring of the Fruit Metabolome in Tomato Breeding. *Cell*, *172*(1), 249-261.e212. https://doi.org/https://doi.org/10.1016/j.cell.2017.12.019

# CHAPTER TWO

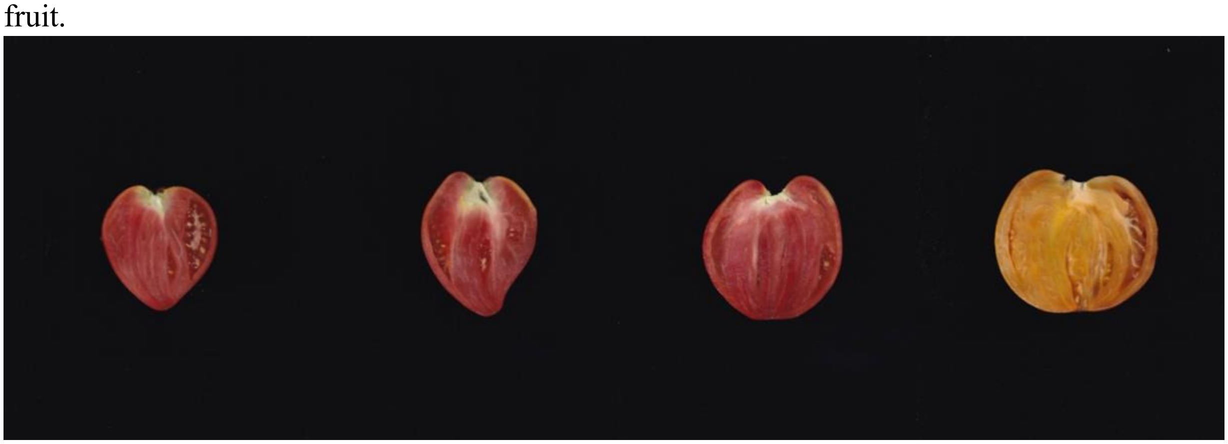
## SCREENING HEART-SHAPED TOMATO CULTIVARS FOR YIELD AND QUALITY PERFORMANCE IN A SHORT GROWING SEASON

### Introduction

Tomatoes (*Solanum lycopersicum*) are one of the most common vegetable crops in the world. In the U.S, tomatoes are the largest vegetable crop in terms of production (USDA, 2025). They are both a grower and consumer favorite, prized for their unique flavors and colorful appearance (Jordan, 2007). Tomatoes are a warm season crop that is extremely frost sensitive making it difficult to grow in regions with short growing seasons and low growing degree days. However, despite the challenges of growing tomatoes in these climates, they remain a valuable crop for vegetable growers producing for local markets and gardeners all around the country. The diversity of tomato cultivars, both open-pollinated and F1 hybrid, is vast, estimated at more than10,000 cultivars today (Benoit, 2023). While there is an abundance of diversity, there is not always information on which cultivars are best suited to specific regions, and there is a need for research into locally adapted tomato varieties, particularly in regions that have a shorter growing season.

Tomato cultivars are classified by shape, size, color, and use or market class, and many growers selling to local markets grow a diverse array of cultivars. Market classes include processing tomatoes, fresh market tomatoes, slicer tomatoes, cherry tomatoes and more. The specific class of tomatoes investigated in this study is the heart-shaped slicer. Heart-shaped slicer tomatoes are typically medium, large or very large tomatoes. They are typically fleshy with few seeds, but don't quite have qualities to be categorized as processing tomatoes. They come in many different colors including red, pink, yellow, orange, brown and striped. Their shape sets them apart from other types of tomato with lofty and smooth shoulders and a pronounced tear-drop shape towards the blossom end. Large heart-shaped tomatoes have been labelled in different ways that all describe the same shape category. They have been described as having cordate, heart-shaped, or oxheart shape (IPGRI, 1996; Rodríguez et al., 2011; UPOV, 2024). This shape is controlled by specific genes; the tomatoes within this shape category carry the LC mutation as well as the FAS and or the SUN mutation (Rodríguez et al., 2011). Although the tomato cultivars in this study were not checked to conform to this genetic categorization, they all fell into the morphological oxheart shape class described in the study by Rodriguez et al. Many cultivars also had 'heart' or 'oxheart' included in the name, which was used in selection for this study.

Figure 1: Some heart-shaped slicer tomatoes from the experiment. From right to left: 'G32329,' 'Cuore di Toro,' 'Wes,' 'Faribo Goldheart.' The heart-shape can be more or less pronounced in fruit.



The heart-shaped cultivars tested in this trial are heirloom, open-pollinated types (older than 50 years) many of which were selected in various parts of Europe and Asia (Table 1). While the history of many cultivars in this study is unknown, we do know that several heart-shaped tomato cultivars that are now available in the U.S. were brought by immigrants from various parts of Europe and eventually were given to seed companies (The Seed Savers Exchange, Tomato Fest, Ohio Heirloom Seeds, Hudson Valley Seed). Several heart-shaped tomato cultivars, and more specifically the oxheart type within the heart-shaped class, were bred in northern regions of Europe and are popular there, particularly in Russia and Ukraine (Table 1; M. Glebov, personal communication, Nov 10 2024; Tomato Bogato n.d.). This means that these cultivars, such as ‘Bull’s Heart’ or ‘Korol Sibiri’ were selected in colder climates and could produce well in Montana where there are about 100 frost free days compared to about 100 days in Novosibirsk, RU and about 135 days in St. Petersburg, RU where some of the cultivars in this study were selected.

In Bozeman and Montana more widely, the short growing season, cool nights, and unpredictable frosts make local production of the cold-sensitive tomato challenging. Nevertheless, consumer demand for tomatoes makes growing them quite lucrative for Montana’s 400 or so vegetable growers. Using a protected environment, like unheated high tunnels, is vital in places with short growing seasons with fewer growing degree days to accumulate heat units for ripening fruit and protecting plants from frost. A number of studies show the yield advantage and increased marketability of tomatoes grown in high tunnels, especially in colder regions (Healy et al., 2017; O’Connell et al., 2012; Rogers & Wszelaki, 2012). Local production makes it possible to sell tomatoes that do not have a long shelf-life, have more flavor potential, and offer a summer delicacy for consumers.

Due to tomato popularity, seed catalogs continue to introduce new tomato cultivars to their catalogs every year, which can make the selection of tomato cultivars for production overwhelming for farmers and gardeners. Niche and heirloom varieties of tomatoes are valued and sought after for their taste, appearance, and fruit quality in local production systems (Jordan, 2007), but without the ability to screen this overwhelming variety of tomatoes, farmers might be disincentivized to look for more flavorful, attractive, and productive tomatoes for their customers that are well adapted to their specific climate.

Meanwhile, the variety of tomatoes offered at American grocery stores for fresh consumption is quite narrow in comparison, featuring only handful of slicers and several different cherry tomatoes. For decades consumers have been dissatisfied with the flavor of hybrid tomatoes offered in grocery stores, with modern commercial tomatoes not having the flavor of older, open-pollinated varieties (Bruhn et al., 1991; Malundo et al., 1995; Tieman et al., 2017). This has greatly increased the demand for heirloom or heirloom-type tomatoes, which are perceived as having better flavor and that people seek out as a gourmet item and farmers can sell at a high price point of $4-$7 per pound or more (Jordan, 2007). As a result, the term ‘heirloom’ has been used as a marketing tactic to sell any tomato, even if it doesn’t fulfill the criteria, but might look like an heirloom, has excellent flavor, a rustic-looking appearance, and one that is typically grown locally (Bryant et al., 2025). This demand can be used by local farmers to explore tomatoes with great flavor and unique appearance and that stray from the traditional round and red tomatoes that consumers are used to in grocery stores.

The goals of modern commercial tomato breeding for fresh market prioritize yield, disease resistance, plant vigor, and longer shelf-life without centering selection for flavor. It has been shown through several studies that tomatoes harvested green for a longer shelf-life make a great sacrifice to flavor as the development of sugars is cut short in the fruit (Diehl et al., 2013; Klein et al., 2010; Resurreccion & Shewfelt, 2006). Also, much of this breeding has focused on large, conventional commercial growers and produced cultivars favorable to those conditions. In 2011, 95% of organic production was based on cultivars bred for conventional, high input systems (Lammerts van Bueren et al., 2011). Some of the key challenges in organic production that could be addressed with specific breeding efforts include nutrient use efficiency, weed competition, tolerance to mechanical weed control, resistance to seed-borne diseases, insects, fungal and bacterial diseases, and tolerance to abiotic stress. It is important to identify tomato cultivars that are more adaptable to local conditions and needs that possess favorable qualities for both producers and consumers through variety trials and future breeding efforts.

In this study we screened open-pollinated, heart-shaped tomatoes with an indeterminate growth habit for high yield, earliness, fruit quality, and disease resistance under organic, covered culture. Many of these varieties fall into the oxheart morphological class and have the common characteristics of being very large, fleshy, with few seeds, and having fresh market eating flavor and texture. They have so few seeds that seed production can be quite difficult (Hudson Valley Seed Company, n.d.; TomatoFest, n.d.), but it makes them appealing for uses such as sandwiches and salsas where seeds are not desirable, but fleshiness is. In addition, the morphological class of heart-shaped slicer tomatoes has not been widely explored through systematic research, which could help inform a wider audience about their characteristics and performance. They have the potential to fill a demand for unique and flavorful tomatoes for local consumption or for local processing as well as providing breeding material for the development of new cultivars for short growing seasons. The heart-shaped tomatoes in this trial were screened using methods emulating the common practices of vegetable growers in the region, using high tunnels and organic practices for production.

Table 1: The origins of some of the tomato cultivars in the experiment that were provided by the seed sources.

| Cultivar | Seed Source | Origins |
|---|---|---|
| Amish Paste | Tomato Growers | Pennsylvania |
| Anna Russian | Tomato Fest | Russia |
| Anthony's Passionate Heart | Tomato Growers | Jeff Dawson, California |
| Black Trifele | Tomato Fest | Russia |
| Brad's Black Heart | Tomato Fest | California |
| Buffalo Heart | Tomato Fest | Poland |
| Buffalo Heart Giant | Tomato Fest | Poland |
| Bull's Heart | Tomato Fest | Russia |
| Corazon de Sadaba | USDA GRIN | Spain |
| Cuore di Toro | USDA GRIN | Italy |
| Dwarf Pink Passion | Tomato Fest | Dwarf tomato project |
| Dwarf Purple Heart | Tomato Fest | Dwarf tomato project |
| Faribo Goldheart | Tomato Fest | Minnesota |
| G32329 | USDA GRIN | Albania |
| German Red Strawberry | Tomato Growers | Germany |
| Giant Of Siebenburgen | Reimer Seeds | Romania |

| | | |
|---|---|---|
| Giant Red Oxheart | Tomato Fest | Kentucky |
| Grightmire's Pride | Reimer Seeds | Yugoslavia |
| Gritmire's Pride | Tomato Fest | Yugoslavia |

Table 1 continued

| | | |
|---|---|---|
| Heart of Sombor | Tomato Fest | Croatia |
| Hogs Heart | Tomato Fest | Italy |
| Hungarian Heart | Tomato Growers | Hungary |
| Il Duce | USDA GRIN | Wyoming, US |
| Japanese Oxheart | Tomato Fest | Japan |
| Kornesevsije | Tomato Fest | Russia |
| Korol Sibiri | Ohio Heirloom Seeds | Siberia, Russia |
| Kosovo | Tomato Growers | Kosovo |
| Kwangtung 120 | USDA GRIN | China |
| Linnie's Oxheart | Tomato Fest | Kentucky |
| Long Portonian | USDA GRIN | United Kingdom |
| Milka's Yugo Ox Heart | The Experimental Farm Network | Yugoslavia |
| Mrs. Houseworth | Tomato Fest | Pennsylvania |
| Orange Russian 117 | Tomato Fest | Jeff Dawson, California |
| Rawlings | Tomato Fest | Kentucky |
| Reif Red Heart | Tomato Fest | Italy |
| Rozovyi Myod "Siberian Pink Honey" | Ohio Heirloom Seeds | Omsk, Russia |
| Russian 117 | Tomato Fest | Russia |
| Strawberry | Ohio Heirloom Seeds | Europe |
| Ukrainian Heart | Hudson Valley Seed | Ukraine |

## Materials and Methods

### Germplasm

Tomato germplasm was obtained from 10 different sources (Table 6 in Supplementals). In the 2024 season, germplasm was collected by getting a large set of tomatoes under the phenotypical classification “heart.” In 2024, 71 tomato cultivars were trialed.

Not all varieties trialed in 2024 were morphologically heart-shaped. In 2025, cultivars that were clearly not “heart-shaped,” or that were cherry or plum-sized were excluded based on 2024 data. This focused the trial on heart-shaped ‘slicer’ tomatoes suited for high tunnel production to be able to better compare yield and quality metrics within one market class of tomatoes. In 2025, three commonly grown F1 hybrid tomatoes were added to the experimental design as a comparison of both yield and quality to the heart-shaped tomatoes. These amendments narrowed the scope of the experiment to 51 varieties in 2025.

### Growing Environment

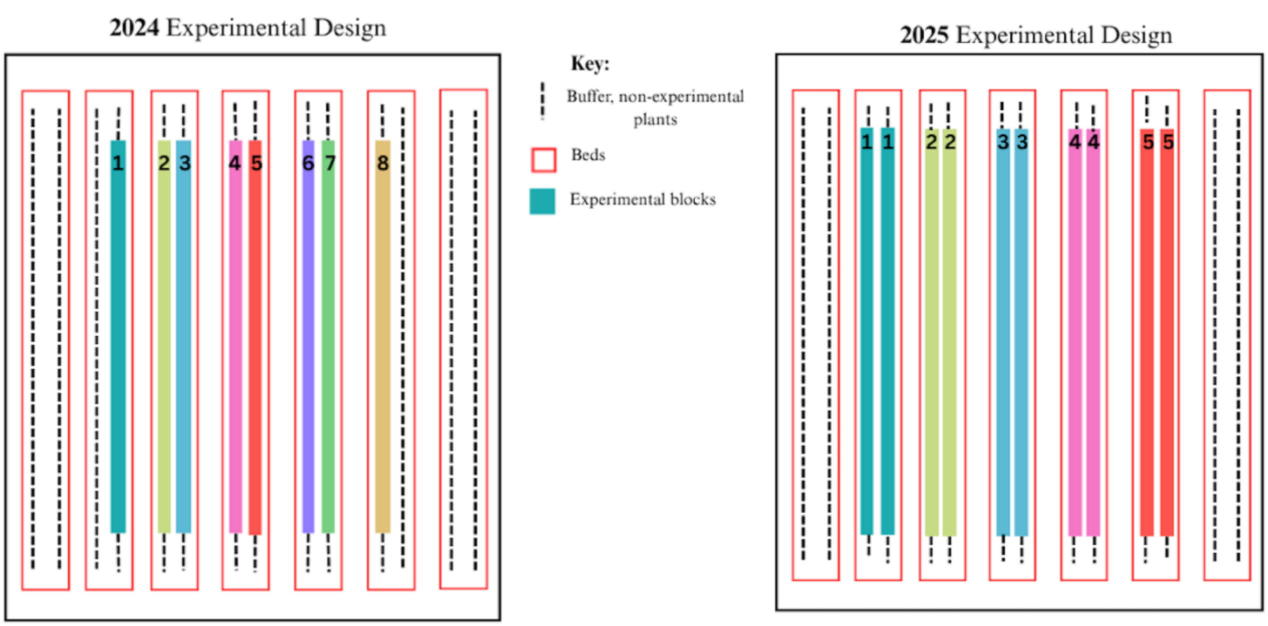
Tomatoes were grown in an unheated high tunnel (30 ft by 48 ft) at 18 inch spacing in both years of the experiment at the Montana State University Horticulture Farm in Bozeman, MT (45.664279°N, 111.074326°W). The last frost date in 2024 was May 23 and the first frost date was October 23. The last frost date in 2025 was April 22 and the first frost was October 6. The growing degree days starting from tomato transplant to termination of the experiment was 840 in

2024 and 907 in 2025. Growing degree days were calculated in Celsius with degrees from average daily temperature over 10°C summed over the season.

Field Techniques

In the 2024 season, varieties were planted in an augmented block design. There were 10 check varieties replicated in each of the 10 blocks, and 61 unreplicated test varieties (Figure 2). Check varieties were chosen based on number of seed available, since there was no knowledge of how any of the varieties might perform. Several check cultivars were also used as test treatments to fill empty space in the experiment.

Figure 2: High tunnel layout of the experiment in with 8 blocks in 2024 and 5 blocks in 2025.




The following season, the change in number of varieties in the design also made it possible to have more replications of each cultivar. The experimental design was changed to create a randomized complete block design with one bed (two rows) of tomatoes being equal to one block replicate. The high tunnel had a total of 5 blocks and therefore 5 replicates of each of the 51 cultivars (Figure 2).

Tomato plants were seeded in a heated greenhouse and watered and fertilized with a fish emulsion fertilizer. Tomatoes were transplanted 7 weeks after the seeding date into the high tunnel on June 12$^{th}$ in 2024 and on May 16$^{th}$ in 2025. High tunnel soil was amended with 13-0-0 bloodmeal pellets at about 150 lbs per acre before landscape fabric and drip system installation. The drip system watered at about 0.17 gallons per hour (GPH) per foot with the plants watered 3 times a week for 2-hour intervals. During the season, plants were regularly pruned and trellised to one leader. Irrigation was stopped in mid-September and the main growth points on plants were pruned at the last fruit set. Vines were picked clean of fruit on September 30 in 2024 and September 22 in 2025 and removed.

Harvest

Tomatoes were harvested when fruit reached at least the “pink stage” or later according to the USDA definition, which means that at least 30% of the total fruit surface was turning from green to the ripe color (USDA, 2004). Fruit were picked twice a week, and tomatoes were individually weighed. During harvest, plant disease, fruit deformity, and pest damage were noted per plant. After the first fall frost, all remaining fruit were harvested and weighed.

Chemical Analysis

The first three fruits were collected from each plant for titratable acidity (TA), soluble solids (°Brix), and dry matter analysis. These fruits were harvested and left to fully ripen off the vine in paper bags. After reaching full ripeness, tomatoes were cut in half with one half of each fruit going to dry matter testing and the other half frozen for titrations and °Brix testing at a later time.

Dry Matter. One half of each tomato was weighed fresh and then dehydrated at 105 °C. Fully dried tomatoes were weighed again with dry weight recorded and dry matter calculated using the formula below:

$$Dry\ matter = \frac{dry\ weight}{wet\ weight}$$

Sugar and Acid Content. The second half of the tomatoes were used to determine titratable acidity and soluble solids content (°Brix). The samples were initially frozen and analyzed after the field season was over.

For analysis, tomatoes were thawed, macerated, and 1.7 mL of the pulp was centrifuged to produce 1 mL of clear juice for °Brix testing using a digital Atago pocket refractometer (Atago, Saitama, Japan). Five grams of the same pulp was titrated in 100 mL of distilled water with 0.1 M sodium hydroxide solution to an endpoint of 8.2 pH using a AT1000 Series Hach TitraLab automatic titrator with a Hach pH probe (Hach, Loveland, USA). The formula below was used to calculate titratable acidity, expressed as percent citric acid, with 0.1 being the NaOH solution normality and 0.064 being the acid equivalent weight of citric acid.

$$TA = \frac{(mL\ NaOH) \times 0.1 \times 0.064}{5} \times 100$$

Stem Diameter

In 2025, a measurement of the diameter of the plants' stems was taken at ground level. These measurements were collected using calipers about 2 cm off the ground. The widest part of the stem at that point was measured and recorded in late September when the growth of the plants had almost stopped.

Firmness

In 2025 season, we also measured fruit firmness using a Lutron FR-5120 digital fruit firmness tester with a 6 mm tip (Lutron Electronic Enterprise, Taipei, Taiwan). The whole fruit was tested for firmness at full ripeness prior to cutting in half for dry matter, titratable acidity, and °Brix analysis. Fruit was tested at three points of the fruit, around the blossom end and at opposite lateral halfway points of the fruit. Peak pressure was measured in Newtons.

Statistical Analysis

Statistical analysis was done using the program R. An ANOVA analysis was used to determine if there is a significant difference between cultivars in qualities and was followed by an LSD post-hoc test. In 2024, the “augmented RCBD” R package (Aravind et al., 2023) was used for analysis using the following linear model equation:

$$y_{ij} = \mu + C_i + G_k + B_j + \varepsilon_{ij}$$

Where $y_{ij}$= response (e.g., yield, TA, °Brix, etc.), $\mu$= overall mean, $C_i$= effect of check cultivars, $G_k$= effect of test cultivars, $B_j$= fixed effect of block, and $\varepsilon_{ij}$= residual error. In 2025 a mixed effects model was used to analyze the data using the “lme4” R package (Bates et al., 2015) using the following linear model equation followed by LSD rankings.

$$y_{ij} = \mu + G_i + B_j + \varepsilon_{ij}$$

Where $y_{ij}$= response (e.g., yield, TA, °Brix, etc.), $\mu$= overall mean, $G_i$= fixed effect of cultivars, $B_j$= random effect of block, and $\varepsilon_{ij}$= residual error.

Overall Cultivar Scoring

In order to assess cultivars' performance with regards fruit quality traits, a combined scoring system using z-scores was used. Mean values for TA and °Brix averaged from both years were standardized using the z-score formula below and then z-scores were weighed equally and summed to give a final score.

$$Fruit\ quality\ score = 0.5 \times \frac{trait\ value - trait\ \bar{x}}{(trait\ s)} + 0.5 \times \frac{trait\ value - trait\ \bar{x}}{(trait\ s)}$$

When assessing cultivars' performance overall, the R package 'metan' was used to create a Multi-Trait Genotype-Ideotype Distance Index (MGIDI). The traits used in this index were yield, TA, °Brix, and firmness which were averages from the two years. The MGIDI Index was weighed towards yield with yield having twice the weight in the index as the other traits.

Sensory Analysis

Sensory analysis surveys were carried out at MSU research farm field days on August 14, 2025 at Corvallis, MT and on August 28, 2025 at Bozeman, MT with voluntary participants from these two public events. On September 4, 2025, students from an MSU Horticulture class voluntarily participated in the sensory survey during class time. Svetlana Frost administered the survey.

Sensory analysis was conducted with a short 9 question, multiple choice paper survey for each of two samples (Appendix). Different cultivars were compared at different tasting events and were chosen based on the cultivars that had the most ripe fruit at the time of the survey. The cultivars compared were ‘Buffalo Heart’ and ‘Red Butterheart,’ ‘Orange Strawberry’ and ‘Huge Lemon Oxheart,’ and ‘Linnie’s Oxheart’ and ‘Kwangtung 120.’ Tomatoes were sliced into bite-size pieces and displayed as sample A or B on individual plates. 7 out of 9 questions asked respondents to select an answer on a scale of 1-5. The surveys asked respondents to evaluate flavor, texture, and appearance of tomato samples and which of two samples respondents preferred. The taste testing protocol #2025-2155 received IRB approval from MSU for a human subjects minimal risk exempt status prior to proceeding with surveying.

## Results

Data from each cultivar for all traits tested is listed in Table 6 in Supplementals.

### Yield

There was a significant difference in yield between tomato cultivars in both years of the experiment (Table 2 and 3). Total yield per plant of a given cultivar based on adjusted means in 2024 was consistently higher than in 2025. There was also a significant block effect on yield in 2024. Cultivars ‘Red Butterheart,’ ‘Russian 117,’ ‘Hungarian Heart,’ ‘Milka’s Yugo Oxheart,’ and ‘Buffalo Heart Giant’ all were part of the top yielding group in both years. In both years, the tomato ‘Bobbie’ yielded the lowest, with one plant in 2025 contracting pythium root rot and not yielding at all.

Table 2: Analysis of variance for tomato cultivar traits from the augmented RCBD design in 2024 adjusted for blocks. Significance based on: ns=No Significance; . <0.1; *<0.05; **<0.01; ***<0.001

| Effect | DF | Yield | TA | pH | °Brix | Fruit Size | Dry matter | DTM |
|---|---|---|---|---|---|---|---|---|
| Cultivar (Ignoring Blocks) | 81 | 1.7E-3 ** | 3.7E-07 *** | 6.1E-05 *** | 1.8E-3 ** | 1.1E-6 *** | 3.0E-61 *** | 5.4E-06 *** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Treatment: Check** | 9 | 3.8E-3 ** | 9.1E-05 *** | 2.4E-4 *** | 0.11 ns | 1.6E-8 *** | 0.72 ns | 4.7E-4 *** |

Table 2 continued

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Treatment: Test** | 71 | 4.2E-3 ** | 9.8E-07 *** | 2.3E-4 *** | 1.5E-3 ** | 1.9E-4 *** | 4.7E-62 *** | 1.2E-05 *** |
| **Treatment: Test vs. Check** | 1 | 0.42 ns | 0.60 ns | 0.23 ns | 0.94 ns | 9.4E-4 *** | 6.5E-21 *** | 0.74 ns |
| **Block (eliminating Treatments)** | 7 | 7.2E-3 ** | 4.7E-3 ** | 0.06 ns | 0.09 ns | 0.90 ns | 0.13 ns | 0.59 ns |

Table 3: Analysis of variance for tomato cultivar traits in 2025 using a mixed effects linear model. Significance based on: ns=No Significance; . <0.1; *<0.05; **<0.01; ***<0.001

| **Effect** | **DF** | **Yield** | **TA** | **pH** | **°Brix** | **Fruit Size** | **Dry matter** | **Firmness** | **DTM** |
|---|---|---|---|---|---|---|---|---|---|
| Cultivar | 50 | 7.5E-4*** | 1.3E-10*** | 3.2E-5*** | 1.4E-4*** | 1.4E-14*** | 3.2E-7*** | 0.003 ** | 2.4E-12*** |

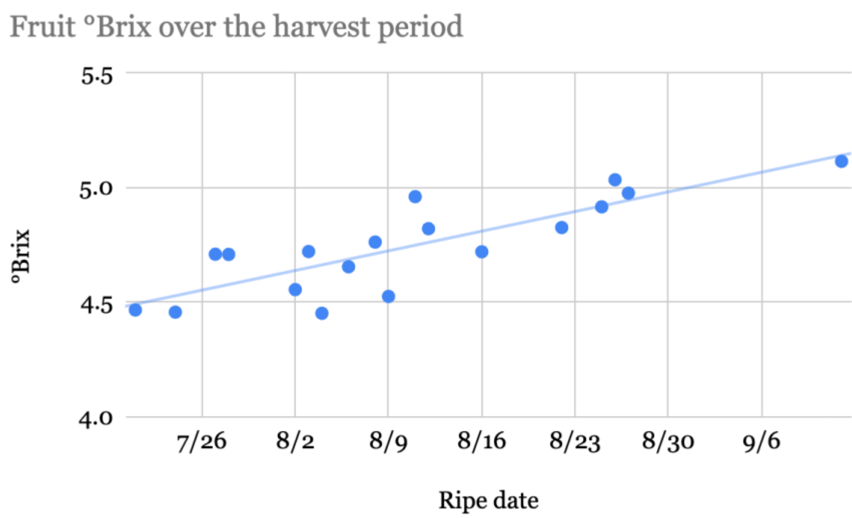
Days to Maturity

Cultivars ‘Anthony’s Passionate Heart,’ ‘Oxheart Pink,’ and ‘Bull’s Heart’ were among the earliest maturing in both years. The earliest tomato in 2024 ripened in 49.2 days from transplant and the earliest in 2025 ripened in 71.2 days from transplant. Days to maturity (DTM) were significantly different between cultivars in both years of the experiment (Tables 2 and 3).

°Brix and Dry Matter

There was a significant difference in fruit °Brix and dry matter between cultivars in both 2024 and 2025. There was no significant difference between different check varieties in °Brix and fruit dry matter, while there was a difference found between check and test treatment in dry matter in 2024 (Tables 2). Cultivars ‘Faribo Goldheart,’ ‘Kwangtung 120,’ ‘Wes’, ‘Rawlings,’ and ‘Kosovo’ were among the highest in °Brix in 2024 and 2025. Cultivars ‘Wes,’ ‘Anna Russian,’ and ‘Brad’s Black Heart’ were among the highest in fruit dry matter in 2024 and 2025. Although most of the dry matter in tomato fruit consists of soluble solids, there was not a strong correlation between the two in 2025 ($r = 0.482$). Fruit °Brix increased on averaged through the 2025 season, with higher fruit °Brix later in the season with genotype disregarded (Figure 3).

Figure 3: Relationship with trendline between tomato fruit °Brix and ripe date regardless of genotype in 2025.

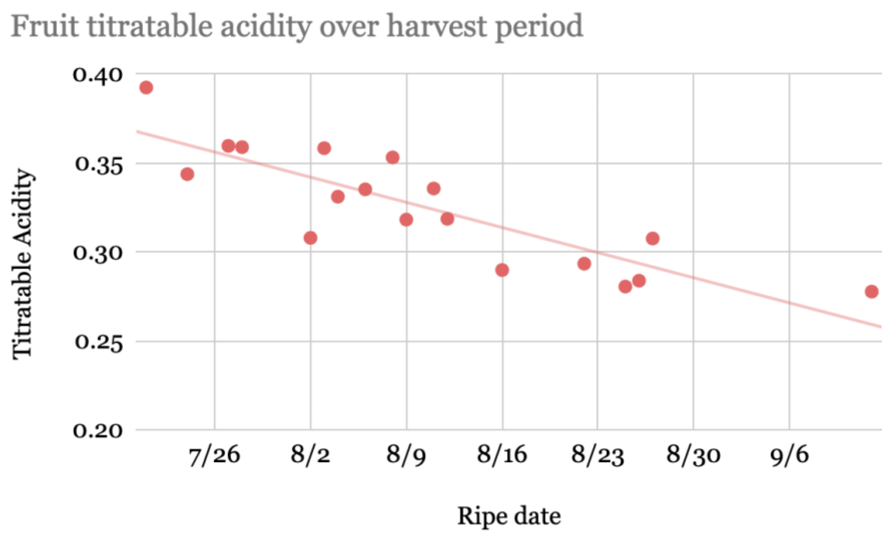



Titratable Acidity and pH

There was a significant difference in fruit titratable acidity and pH between cultivars in both 2024 and 2025. There was also a significant block effect on titratable acidity in 2024 (Tables 2 and 3). Cultivars ‘Brad’s Black Heart’ and ‘Wes’ were among the highest in titratable acidity in 2024 and 2025. Cultivars ‘Faribo Goldheart’ and ‘Cuore di Toro’ were among the lowest in fruit pH in 2024 and 2025. The correlation between fruit titratable acidity and pH in

2025 was mild, with the coefficient of correlation r = -0.635. Fruit TA decreased on averaged through the 2025 season, with lower TA later in the season when genotype was excluded (Figure 4).

Figure 4: Relationship with trendline between tomato fruit TA and ripe date regardless of genotype in 2025.




<u>Stem Diameter</u>

Stem diameters of vines ranged from 8.6 mm to 17.2 mm. There was no significant correlation between stem diameter and plant yield (r=0.245).

<u>Disease and Deformity</u>

Cultivars were mainly screened for disease and deformity in the randomized complete block design in 2025. Two plants of the cultivars ‘Bobbie’ and ‘Wes’ were stunted by pythium and fusarium root rot. No other tomatoes showed significant signs of disease other than some heat and water stress starting mid-season. There was a significant difference found in cultivars that had instances of fruit deformity ($p<0.015$). The fruit deformity that was found included blossom end rot, scarring, cracking, and cat-facing. The cultivars that showed instances of any of these in 4 or more blocks were ‘Corazon de Sadaba,’ ‘Linnie’s Oxheart,’ ‘Orange Russian 117,’ and ‘Oxheart Pink.’

## Sensory Survey Results

For the three comparisons done in the sensory analysis portion of this project, the survey comparing cultivars ‘Buffalo Heart’ and ‘Red Butterheart’ got 48 respondents, ‘Huge Lemon Oxheart’ and ‘Orange Strawberry’ got 36 respondents, and ‘Linnie’s Oxheart’ and ‘Kwangtung 120’ got 51 respondents. Only one survey comparing ‘Huge Lemon Oxheart’ to ‘Orange Strawberry’ found significant differences in preference for one cultivar compared to another with respondents significantly preferring ‘Huge Lemon Oxheart’ ($p<0.002$).

## Scoring and Comparisons

To find which cultivars performed well with regards to fruit quality, a score based on z-score and weighted equally for titratable acidity and °Brix was created (Table 4). Next, highest ranking cultivars are listed in Table 5 based on a MGIDI Index based on yield, TA, °Brix, and firmness, weighted more heavily towards yield. Cultivars ‘Oxheart Pink’ and ‘Orange Russian 117’ marked in Tabe 5, were cultivars that had substantial occurrence of fruit deformity in 2025.

Table 4: Top ranking tomato cultivars in descending order based on a score with 50% weighted towards titratable acidity and 50% to °Brix with data averaged from both years.

| **Treatment** | **Score, TA and °Brix** |
|---|---|
| Wes | 2.0 |
| Faribo Goldheart | 1.8 |
| Brad's Black Heart | 1.7 |
| Gritmire's Pride | 1.1 |

| | |
|---|---|
| Thieneman's Austrailian Heart | 1.0 |
| Rawlings | 0.9 |
| Anthony's Passionate Heart | 0.6 |
| Hungarian Heart | 0.6 |

Table 4 continued

| | |
|---|---|
| Anna Russian | 0.3 |
| Giant Syrian | 0.3 |

Table 5: Top ranking tomato cultivars in order based on the Multi-Trait Genotype-Ideotype Distance Index (MGIDI) using R package "metan" with scoring based on averaged yield, TA, °Brix, and firmness from both years. Scoring is weighed more heavily on yield than on other traits.

| **Treatment** | **MGIDI Index** |
|---|---|
| Cuore di Toro | 0.03 |
| Strawberry | 0.10 |
| Oxheart Pink * | 0.12 |
| Reif Red Heart | 0.27 |
| Rozovyi Myod "Siberian Pink Honey" | 0.32 |
| Korol Sibiri | 0.38 |
| G32329 | 0.40 |
| Buffalo Heart | 0.43 |
| Orange Russian 117 * | 0.43 |
| Ukrainian Heart | 0.48 |

## Discussion

The results of this study found cultivars that performed well in both years of the experiment even with different designs and conditions. In 2025, yield, some quality traits, and appearance of disease and deformity were poorer than in 2024 due to some mismanagement of irrigation and poor ventilation of the high tunnel during a hot period in June. Nevertheless, the management was the same with regards to the whole high tunnel in a given year, so cultivars that were higher performing were still identified and the cultivars susceptible to disease or quality issues observed.

In both years, genotype had a significant effect on all traits screened. There was a significant block effect on yield as well as titratable acidity in 2024. The differences in yield can be explained by the block's location in the greenhouse and small variations in those conditions, with block 2 having the highest yield and block 7 the lowest. Titratable acidity can also be affected by environmental differences between blocks in various parts of the high tunnel (Zheng et al., 2022). Additionally, based on the data shown in Figures 3 and 4, environmental differences through the growing season made an impact on fruit quality, with the fruit harvested from the experiment in the beginning of the season having lower °Brix and higher TA and then higher in °Brix and lower in TA in the end of the season.

The earliness of cultivars when measured in days to maturity was quite different between the two years of the experiment (about 50 days compared to 70 days). This could potentially be explained by the difference in planting dates of the two years. Plants in 2025 were planted about a month earlier than in 2024, meaning that they spent the cooler month of May in the ground, while plants in 2024 were transplanted in June when it got warm shortly, the plants started to grow immediately. First harvests still started about 2 weeks earlier in 2025 with the earlier planting date, although they took more days to mature from transplant.

After the collection of all performance and quality traits for cultivars in both years, data from the two years was averaged and then used to create z-scores for TA and °Brix traits to create an equally weighted, combined score of a cultivar's fruit flavor quality. Titratable acidity and °Brix are considered the measures of sweetness and acidity that are most correlated to consumer taste and flavor perception (Baldwin et al., 2008; Tandon et al., 2003), so these were the measurements chosen to evaluate a cultivar's flavor. As seen from the correlation coefficients of pH and TA and dry matter and °Brix, the correlation was between those traits was not very strong in this experiment, leading to just TA and °Brix being chosen for flavor quality analysis. In order to get more insights on cultivars' fruit flavor, the sensory survey was undertaken on 4 different occasions comparing two samples. Six cultivars were compared overall during these survey sessions, but only one comparison showed a significant difference in participants' preferences. 'Huge Lemon Oxheart' was significantly preferred with regards to flavor, texture, and appearance over 'Orange Strawberry' ($p<0.002$). 'Huge Lemon Oxheart' had a stronger flavor with higher measurements of °Brix and titratable acidity in 2024 and during the survey in 2025, participants noted that 'Huge Lemon Oxheart' was more flavorful than 'Orange Strawberry'.

The MGIDI Index was used to rank the performance of all cultivars with regards to chosen traits. Yield, TA, °Brix, and firmness were chosen to be used for that ranking. Although days to maturity has an important implication to growers who want to offer tomatoes to consumers as early as possible, this was not included in the final overall ranking because of the vastly differing numbers between the two years. This information can be seen separately in Table 6. Firmness was included with yield and flavor traits as it is an important market trait both for longer shelf-life of these tomatoes as well as better transportability. It was also a characteristic that was deemed important after the 2024 season when a number of cultivars clearly lacked desirable firmness when marketed. The cultivars that performed best with regards to all these traits were ‘Kwangtung 120,’ ‘Thieneman’s Australian Heart,’ ‘Wes,’ ‘Rawlings,’ and the others shown in Table 5 of the Results. The tomato ‘Huge Lemon Oxheart’ was part of the highest-ranking cultivars using the MGIDI Index and was also the only cultivar that was significantly preferred in the sensory surveys. This shows that the chemical analysis used was supported by sensory analysis with both being favorable for this cultivar.

As well as narrowing the scope of the experiment overall to cultivars that were slicer sized, heart-shaped, indeterminate, and open-pollinated, the 3 hybrid cultivars added for comparison gave some interesting insights. ‘Big Beef Plus F1’ and ‘GinFiz F1’ were among the highest yielding group in 2025 based on LSD significance rankings. They were both in the highest group for firmness and in the top scoring group for titratable acidity and °Brix weighed equally for each in 2025. ‘Abigail F1’ did not perform quite as well all around. Nonetheless, neither of these hybrids significantly exceeded the open-pollinated varieties with regards to any trait or performance overall.

One observation made on a number of these cultivars is that the plants are often quite wispy and thin especially in comparison to the hybrids (LeHoullier, 2015). Nevertheless, no significant correlation was found between the stem diameter and plant yield in this study. In conclusion, the wispy and thin appearance of the plants is not predictive of poor yield.

The cultivar ‘Cuore di Toro’ was all around a good performer, with high yields and robust flavor as well as early yields compared to others. Another tomato that was exceptional in flavor based on chemical analysis as well as being an early bearer was ‘Anthony’s Passionate Heart.’ This cultivar was not the highest yielding, but had particularly early, large, and flavorful fruit. The cultivars listed in Table 4 would be the choice for a grower who is looking for intense and robust tomato flavor, where there are top scoring cultivars with regards to titratable acidity and °Brix and include red, pink, yellow, and black-pink cultivars. Table 5 gives a variety of cultivars that performed well with regards to traits all around and have robust flavor and high yields but may not be as flavorful or intense as ones listed in Table 4.

A number of cultivars in this study showed more short-season adaptability than others, with higher yield and better performance in fruit quality. The wide range of cultivars screened also produced a great range of different yields and qualities and the data collected in this study could be used to choose a cultivar that fits a grower’s specific needs whether there is a greater interest in fruit quality, DTM or yield. The distinctive shape and quality traits of heart-shape tomatoes could be of interest to local growers to fulfill the demand for flavorful and unique heirloom tomatoes while also growing well in a short and challenging season. This data combined with the screening for deformity can also help eliminate cultivars that were not well suited to our growing conditions and the needs of growers. Further, the qualities of these tomatoes such as fleshiness, few seeds, unique shape and size can provide materials for processed, value-add products as well as for breeders to create new cultivars.

# REFERENCES CITED

Andelini, M., Major, N., Išić, N., Kovačević, T., Ban, D., Palcic, I., Radunic, M., & Goreta Ban, S. (2023). Sugar and Organic Acid Content Is Dependent on Tomato (Solanum Lycoperiscum L.) Peel Color. *Horticulturae*, *9*, 313. https://doi.org/10.3390/horticulturae9030313

Avdikos, I. D., Tagiakas, R., Tsouvaltzis, P., Mylonas, I., Xynias, I. N., & Mavromatis, A. G. (2021). Comparative evaluation of tomato hybrids and inbred lines for fruit quality traits. *Agronomy*, *11*(3), 609. https://www.mdpi.com/2073-4395/11/3/609

Baldwin, E. A., Scott, J. W., Einstein, M. A., Malundo, T. M. M., Carr, B. T., Shewfelt, R. L., & Tandon, K. S. (1998). Relationship between sensory and instrumental analysis for tomato flavor. *Journal of the American Society for Horticultural Science*, *123*(5), 906-915. https://doi.org/10.21273/jashs.123.5.906

Behera, S., Mahapatra, A., Rath, A., & Sethy, P. (2019). Classification & grading of tomatoes using image processing techniques.

Benoit, D. J. (2023, February 8). *A history of tomatoes*. University of Vermont Extension. A history of tomatoes

Brezhnev, D. D. (1955). *Томаты [Tomatoes]* (L. a. Brozheyt, Ed.). The State Publishing of Agricultural Literature.

Bruhn, C. M., Feldman, N., Garlitz, C., Harwood, J., Ivans, E., Marshall, M., Riley, A., Thurber, D., & Williamson, E. (1991). Consumer perceptions of quality: apricots, cantaloupes, peaches, pears, strawberries, and tomatoes. *Journal of Food Quality*, *14*(3), 187-195. https://doi.org/https://doi.org/10.1111/j.1745-4557.1991.tb00060.x

Bryant, G., et al. (2025). "Identification of Promising Heirloom Tomato Varieties for Production in Hawaii." HortTechnology **35**(2): 241-248.

Davies, J. N. and G. E. Hobson (1981). "The constituents of tomato fruit: the influence of environment, nutrition, and genotype." CRC critical reviews in food science and nutrition **15**(3): 205-280.

De Bruyn, J. W., Garretsen, F., & Kooistra, E. (1971). Variation in taste and chemical composition of the tomato (Lycopersicon esculentum Mill.). *Euphytica*, *20*(2), 214-227. https://doi.org/10.1007/BF00056081

Diehl, D., et al. (2013). "Exploring produce industry attitudes: Relationships between postharvest handling, fruit flavor, and consumer purchasing." HortTechnology **23**: 642-650.

Healy, G. K., Emerson, B. J., & Dawson, J. C. (2017). Tomato variety trials for productivity and quality in organic hoop house versus open field management. *Renewable agriculture and food systems*, *32*(6), 562-572. https://doi.org/10.1017/S174217051600048X

Hudson Valley Seed Company. (n.d.). *Upstate Oxheart tomato*. https://hudsonvalleyseed.com/products/upstate-oxheart-tomato

Hyman, C. (2019). *Tomato : A Global History*. Reaktion Books, Limited. http://ebookcentral.proquest.com/lib/montana/detail.action?docID=5839385

IPGRI. (1996). *Descriptors for Tomato (Lycopersicon spp.)*.

Jenkins, J. A. (1948). "The Origin of the Cultivated Tomato." Economic botany **2**(4): 379-392.

Jordan, J. (2007). The heirloom tomato as cultural object: investigating taste and space. *Sociologia Ruralis*, *47*, 20-41. https://doi.org/10.1111/j.1467-9523.2007.00424.x

Kader, A. A., Stevens, M. A., Albright-Holton, M., Morris, L. L., & Algazi, M. (1977). Effect of Fruit Ripeness when Picked on Flavor and Composition in Fresh Market Tomatoes1. *Journal of the American Society for Horticultural Science*, *102*(6), 724-731. https://doi.org/10.21273/jashs.102.6.724

Klein, D., Gkisakis, V., Krumbein, A., Livieratos, I., & Köpke, U. (2010). Old and endangered tomato cultivars under organic greenhouse production: effect of harvest time on flavour profile and consumer acceptance. *International Journal of Food Science & Technology*, *45*(11), 2250-2257. https://doi.org/https://doi.org/10.1111/j.1365-2621.2010.02398.x

Kong, Y., Llewellyn, D., & Zheng, Y. (2020). High tunnels without anti-insect netting benefit organic cherry tomato production in regions with cool and short growing seasons. *Canadian journal of plant science*, *100*(4), 401-414. https://doi.org/10.1139/cjps-2019-0243

Lammerts van Bueren, E. T., Jones, S. S., Tamm, L., Murphy, K. M., Myers, J. R., Leifert, C., & Messmer, M. M. (2011). The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: A review. *NJAS - Wageningen journal of life sciences*, *58*(3), 193-205. https://doi.org/10.1016/j.njas.2010.04.001

Latino, M. E., Menegoli, M., & Corallo, A. (2023). Relevant attributes influencing consumers' tomato acceptance: A systematic review and research agenda. *Journal of agricultural & food industrial organization*, *21*(2), 129-146. https://doi.org/10.1515/jafio-2021-0047

Malundo, T. M. M., Shewfelt, R. L., & Scott, J. W. (1995). Flavor quality of fresh tomato (Lycopersicon esculentum Mill.) as affected by sugar and acid levels. *Postharvest Biology and Technology*, *6*, 103-110.

Mattoo, A., & Razdan, M. K. (2007). *Genetic improvement of solanaceous crops. Volume 2, Tomato* (1st ed.). Science Publishers. https://doi.org/10.1201/b10744

McEvoy, M. (2016). *Understanding the USDA Organic Label*. USDA.

Monforte, A. J., Diaz, A., Caño-Delgado, A., & van der Knaap, E. (2014). The genetic basis of fruit morphology in horticultural crops: lessons from tomato and melon. *Journal of experimental botany.*, *65*(16), 4625-4637. https://doi.org/10.1093/jxb/eru017

O'Connell, S., Rivard, C., Peet, M. M., Harlow, C., & Louws, F. (2012). High tunnel and field production of organic heirloom tomatoes: Yield, fruit quality, disease, and microclimate. *HortScience horts*, *47*(9), 1283-1290. https://doi.org/10.21273/hortsci.47.9.1283

Resurreccion, A. V. A., & Shewfelt, R. (2006). Relationships between sensory attributes and objective measurements of postharvest quality of tomatoes. *Journal of food science*, *50*, 1242-1245. https://doi.org/10.1111/j.1365-2621.1985.tb10452.x

Rodríguez, G. R., Muños, S., Anderson, C., Sim, S.-C., Michel, A., Causse, M., Gardener, B. B. M., Francis, D., & van der Knaap, E. (2011). Distribution of SUN, OVATE, LC , and FAS in the tomato germplasm and the relationship to fruit shape diversity. *Plant physiology.*, *156*(1), 275-285. https://doi.org/10.1104/pp.110.167577

Rogers, M. A., & Wszelaki, A. L. (2012). Influence of high tunnel Production and planting date on yield, growth, and early blight development on organically grown heirloom and hybrid tomato. *HortTechnology (Alexandria, Va.)*, *22*(4), 452-462. https://doi.org/10.21273/HORTTECH.22.4.452

Romdhane, A., Riahi, A., Piro, G., Lenucci, M. S., & Hdider, C. (2023). Agronomic performance and nutraceutical quality of a tomato germplasm line selected under organic production system. *Horticulturae*, *9*(4), 490. https://doi.org/10.3390/horticulturae9040490

Rytov, M. V. (1916). Томат в Северной Полосе Огородничества [The Tomato in Northern Horticultural Regions]. *The Agricultural Library*, 36.

Saavedra, T. M., Figueroa, G. A., & Cauih, J. G. D. (2017). Origin and evolution of tomato production Lycopersicon esculentum in México. *Ciência rural : revista científica do Centro de Ciências Rurais da Universidade Federal de Santa Maria.*, *47*(3), 20160526. https://doi.org/10.1590/0103-8478cr20160526

Smith, A. F. (1994). The Tomato in America: Early History, Culture, and Cookery. Columbia, South Caroline, University of South Carolina Press.

Stevens, M., Kader, A., & Albright, M. (1979). Potential for increasing tomato flavor via increased sugar and acid content. *J. Amer. Soc. Hort. Sci.*, *104*, 40-42. https://doi.org/10.21273/JASHS.104.1.40

Tandon, K. S., Baldwin, E. A., Scott, J. W., & Shewfelt, R. L. (2003). Linking sensory descriptors to volatile and nonvolatile components of fresh tomato flavor. *Journal of food science*, *68*(7), 2366-2371. https://doi.org/10.1111/j.1365-2621.2003.tb05774.x

Tieman, D., Bliss, P., McIntyre, Lauren M., Blandon-Ubeda, A., Bies, D., Odabasi, Asli Z., Rodríguez, Gustavo R., van der Knaap, E., Taylor, Mark G., Goulet, C., Mageroy, Melissa H., Snyder, Derek J., Colquhoun, T., Moskowitz, H., Clark, David G., Sims, C., Bartoshuk, L., & Klee, Harry J. (2012). The chemical interactions underlying tomato flavor preferences. *Current Biology*, *22*(11), 1035-1039. https://doi.org/10.1016/j.cub.2012.04.016

Tomato Bogato. (n.d.). *Bull's Heart.* https://tomato-bogato.ru/product/byche-serdcze-vir/

TomatoFest. (n.d.). *Heart shaped tomatoes*. https://www.tomatofest.com/Heart_Shaped_Tomatoes_s/64.htm

UPOV. (2024). Guidelines for the conduct of tests for distinctiveness, uniformity and stability (tomato). *UPOV, Geneva*, p.17-35.

USDA. (2020). *Potatoes and tomatoes are the most commonly consumed vegetables*. USDA. https://www.ers.usda.gov/data-products/chart-gallery/chart-detail?chartId=58340

USDA. (2025). *Vegetables 2024 Summary*. (0884-6413). USDA

Van Ploeg, D., & Heuvelink, E. (2005). Influence of sub-optimal temperature on tomato growth and yield: a review. *The Journal of Horticultural Science and Biotechnology*, *80*(6), 652-659. https://doi.org/10.1080/14620316.2005.11511994

Wang, S., Qiang, Q., Xiang, L., Fernie, A. R., & Yang, J. (2022). Targeted approaches to improve tomato fruit taste. *Horticulture Research*, *10*(1). https://doi.org/10.1093/hr/uhac229

Wellington, R. (1912). Influence of crossing in increasing the yield of tomato. *Bulletin by New York Agricultural Experiment Station*(No. 346).

Wu, S., Xiao, H., Cabrera, A., Meulia, T., & Knaap, E. (2011). SUN regulates vegetative and reproductive organ shape by changing cell division patterns. *Plant physiology*, *157*, 1175-1186. https://doi.org/10.1104/pp.111.181065

Zhu, G., Wang, S., Huang, Z., Zhang, S., Liao, Q., Zhang, C., Lin, T., Qin, M., Peng, M., Yang, C., Cao, X., Han, X., Wang, X., van der Knaap, E., Zhang, Z., Cui, X., Klee, H., Fernie, A. R., Luo, J., & Huang, S. (2018). Rewiring of the Fruit Metabolome in Tomato Breeding. *Cell*, *172*(1), 249-261.e212. https://doi.org/https://doi.org/10.1016/j.cell.2017.12.019

# APPENDIX

## SENSORY BALLOT FOR HEART TOMATOES

**Sensory Ballot for Heart Tomatoes**

IRB Protocol: #2025-2155

**Section 1 – Appearance and flavor**

Please score your liking of the presented samples on a scale of 1-5, with 1= “dislike extremely”, 3= “neither like nor dislike” and 5= “like extremely”.

**Look at the sample, how do you like the appearance of the sample?**

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| *Dislike extremely* | | *Neither like nor dislike* | | *Like extremely* |

**How much do you like the flavor of the sample?**

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| *Dislike extremely* | | *Neither like nor dislike* | | *Like extremely* |

**How much do you like the texture of this sample?**

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| *Dislike extremely* | | *Neither like nor dislike* | | *Like extremely* |

**How much do you like this sample overall?**

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| *Dislike extremely* | | *Neither like nor dislike* | | *Like extremely* |

**Section 2**

Second, please rate the following texture and flavor attributes of the presented samples on a just about right scale with 1= “Much Too Little”, 3= “Just About Right”, and 5= “Much too Much”

**How would you rate the sweetness of this sample?**

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| *Not nearly sweet enough* | *Not sweet enough* | *Just about right* | *Too sweet* | *Much too sweet* |

**How would you rate the acidity of this sample?**

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| *Not nearly sour enough* | *Not sour enough* | *Just about right* | *Too sour* | *Much too sour* |

**How would you rate the overall texture of this sample?**

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| *Dislike extremely* | | *Neither like nor dislike* | | *Like extremely* |

**Section 3**

**Please check all that apply to the sample.**

- ◻ Dry
- ◻ Mealy
- ◻ Soft
- ◻ Juicy
- ◻ Mild
- ◻ Aromatic
- ◻ Meaty
- ◻ Mushy
- ◻ Other (please specify)

**Section 4**

After filling out the ballot for the other sample, circle the sample that you preferred.

Sample A Sample B