Preharvest factors affecting quality of green asparagus (*Asparagus officinalis*)

- Asparagus spears intended for fresh consumption

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Independent project • 15 credits
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Hortonomprogrammet
Alnarp 2025

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Faktorer före skörd som påverkar kvalitén hos grön sparris (Asparagus officinalis)

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Credits:	15 hp
Level:	G2E
Course title:	Independent project in biology
Course code:	EX0855
Programme/education:	Hortonomprogrammet
Course coordinating dept:	Department of Biosystems and Technology
Place of publication:	Alnarp
Year of publication:	2025

Keywords:	Asparagus, Preharvest, Postharvest, Quality

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Abstract

Asparagus officinalis is an edible immature shoot cultivated all over the world and sold as a seasonal delicacy. Harvest season in Sweden stretches from between 8 to 12 weeks and these local spears are often considered to be of hight quality among consumers. However, clarification as to how different factors affects asparagus spear quality can be beneficial to maintain acceptable standards, and to solve future challenges which may arise with changed weather patterns due to climate change. This paper is a literature study, discussing factors before harvest that can affect quality of green asparagus from a Swedish perspective. How climate change may alter future field conditions in Sweden and hence spear quality is also included.

Asparagus physiology affected mostly textural quality since the bottom section was more fibrous and lignified than the immature top section. Harvested spear diameter affected quality by having more portions of fibrous and lignified tissue in relation to volume, while tall spears had more concentration of fibre compared to shorter ones, and higher rate of respiration which reduced shelf life after harvest. Hence, thick and short spears were more desirable according to literature. However, it was unclear at what height and thickness the textural quality would become undesirable from a consumer perspective, since there seems to be a market even for thin spears.

Agronomical factors such as plant age, root crown depth and density influences quality. Plants produce thinner spears as the plants ages if fern growth and carbohydrate accumulatio is not optimised. Spear diameter would increase with crown depth, spear diameter, while adding more plants per field area had an opposite effect. However, future weather patterns with increased precipitation during fall could require a shallower planting of crowns for optimal drainage, with the possible cost of reduced thickness. Meanwhile, an expected increase of hot summers and periods of drought could require producers to utilise field irrigation in the future, an uncommon practise in Sweden. Shoots need adequate moisture for optimal quality since this adds to spear weight, reduced wilting and contributes to textural tenderness.

Cold field temperatures would also increase the fiber to volume ration, adding to textural toughness, but shelf life as a function of respiration rate, wilting, and tip rot, was prolonged in spears grown during mild weather. Respiration and elongation rate accelerates as field temperature rises, and increases the occurrences of spears with feathered tips, while reducing textural toughness. Spears grown during warm weather are taller and thinner, which contributes to the faster loss of water and sugars, leading to less days of shelf life. Hence, a higher frequency of hot summers could lead to spears of poor visual quality and reduced shelf-life, requiring producers to better monitoring stalks on the field and harvest more often to prevent lanky shoots.

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1. Introduction

1.1 Swedish green asparagus production

Asparagus officinalis L. is a perennial herb and a highly valuable and nutritious vegetable crop (Techavuthiporn & Supapvanich 2020) (see figure 1). Green asparagus stems are consumed all over the world mainly as a fresh commodity (Cannock 2011). The leading producer of asparagus in Europe is Germany, with over 100,000 tonnes of white and green asparagus in 2022 and a harvest area of about 21,300 ha (FreshPlaza 2023).

The Swedish asparagus harvest is significantly lower, with a harvest area of only 139 ha in 2022, which is mainly assigned to the production of green stalks (Jordbruksverket 2023). However, the production has slowly increased over an 8-year period, with 200 tonnes being harvested in spring/summer of 2014, to 300 tonnes in 2022. Spears are imported from southern Europe and South America during off-season in Sweden, to provide a year-round availability of asparagus.

Fig. 1, Asparagus spear emerging from the soil (Anrita, 2020, used with licenced permission from pixabay).

1.2 Improvements of Swedish green asparagus production - The Asparagus project

The **Asparagus project 2017** (Sparrisprojektet 2017), was a collaboration between The Rural Economy and Agricultural Societies in Sweden (Hushållningssällskapet, Skåne), and the Swedish University of Agricultural Sciences (SLU), financed by "Tillväxt Trädgård". The aim of the project was to gather knowledge concerning green asparagus production, that may help increase the yield and profits of the crop in Sweden (Tönnberg et al. 2018). A group of local asparagus producers acted as key members of the project, with the input of knowledge and the assistance to define significant issues and knowledge gaps concerning asparagus production.
Students from SLU were also invited to contribute to the gathering of information and research that may fill in the knowledge gaps concerning the topic.

1.2.1 Implications of spear quality and potential future challenges

Quality of harvested shoots was not identified as a main issue among the participating Swedish producers. The harvest season only stretches over 8 to 12 weeks in Sweden (Tönnberg et al. 2018), and spears are consumed within a few days after harvest, reducing the deterioration of shoots that might be unacceptable for buyers.

However, gathering knowledge about factors affecting quality may help maintain good spear quality and identify potential future quality issues that could arise due to agricultural and environmental factors. For example, such potential future problems may arise from altered weather patterns caused by climate change. Global temperatures are increasing, with heat records broken every year. Extreme and irregular weather patterns are already affecting asparagus in Europe, due to heat waves, drought and flooding. One example of this is the asparagus yield of the previous harvest season of 2024 in Germany and the Netherlands, which was significantly reduced compared to previous year due to waterlogged soils caused by heavy rain (Butler & Dubon 2024, Fruitnet 2024). The future weather in Sweden is predicted to be periodically wetter during fall, winter and spring time, and at the same time prolonged drought conditions are expected to increase during the summer (WWF 2024, Naturvårdsverket, 2024).

Thus, the final quality of the asparagus spear at the consumer market is dependent on factors occurring during growth on the field, as well as right before and after harvest during storage and distribution.

1.3 The definition of quality

The term "**quality**" of a horticultural product may include diverse definitions and meanings depending on the nature of the commodity, its uses and the perspective of the consumer or producer. For a costumer perspective, Kays (1991) identified two main classifications that apply for edible products: nutritional and sensory quality, where sensory quality includes visual appearance, texture, aroma and taste. These attributes are judged by the consumer at the time of purchase, and consumption, and the quality is evaluated through the different characteristics that together determine the acceptability of the product. Visual appearance is probably the most important quality trait, because it is the first characteristics noticed by the consumer (Lill 1980).

For a producer's perspective the quality parameters both include those that affect the customers' buying decisions, but also traits that are important during production and handling before arrival to the final buyer. Such characteristics include storage life and yield, as measured by weight and number of spears harvested (Waldron et al. 2003).

In addition to this, UN (United Nations) and EU (The European Union) have certain marketing standards concerning quality for different food items such as asparagus that needs to be fulfilled concerning certain quality attributes. These include spear size, overall cleanness and visual quality characteristics (Siomos 2018).

1.4 Aim/objectives and limitations

This paper will focus on agricultural and environmental factors residing before harvest (preharvest) and physiological attributes of asparagus itself, that impact the quality of the green asparagus shoots intended for fresh consumption. Quality attributes of discussion will be limited to texture, visual quality and shelf life. Factors not included in this paper are soil properties on the field, fertilization and genetic causes of spear quality.

Questions to be discussed are:

Which physiological, agricultural and environmental factors are the main contributors to the quality of the harvested green shoots?

How do these factors influence the spear quality?

How might altered weather patterns with extreme weather conditions alter future spear quality?

A short introduction about the asparagus plant and relevant spear quality attributes, as well as official marketing standards, will be provided before addressing the main topic.

2. Materials and methods

This paper is a literature study where current knowledge and information on the topic will be provided from scientific papers, journals, newsletters, magazines and books. Scientific search tools being **Google Scholar** and **Web of Science**, will be used combined with the SLU database **Primo** to find sources of scientific literature. Keywords applied are “Green asparagus quality”, “Preharvest”, “Environmental factors” and “Agricultural factors”. A report provided by **Tillväxt trädgård** concerning the asparagus project and a review of the current knowledge about asparagus production, was also used to complement the literature research.

Newsletters will be searched for by using regular **Google,** and to explore relevant statistics and information. The **Asparagus world** magazine along with **Fresh Plaza** have been used to look up news concerning asparagus production in Europe. Additional information is extracted form official websites and reports from Swedish governmental agencies such as **Jordbruksverket** (Swedish Board of Agriculture) and **Naturvårdsverket** (The Swedish Environmental Protection Agency).

3. Results

3.1 Asparagus- an introduction

The asparagus plant part used for consumption is an immature actively growing shoot (Lill & Borst 2001). The stalk is covered with scale leaves at the top which enclose and protects the embryonic branches, known as the lateral buds (see figure 2) (Lipton 1990). If left unharvested, the shoot develops into a mature stem bearing a photosynthesizing foliage called the fern which emerges from the lateral buds in the spear tip (Bhowmik & Matsui 2003, Martin & Hartmann 1990). The foliage contains the small needle-like leaves called the cladophylls, which conduct the photosynthetic process where light energy from the sun is harvested to generate energy-rich compounds and building blocks for the plant (Lipton 1990). The young edible shoots are harvested when reaching a length of approximately 20-25 cm, and when the mature stem is fully grown, the asparagus plant can measure up to 1.5- 2 meters high with the fern included (Tönnberg et al. 2018).

Asparagus officinalis is a dioecious plant, meaning that the species produces either entirely male or female individuals, however asparagus varieties used for commercial production are all male (Drost 2023). The reason for this is because shoot emergence occurs earlier compared to female plants, they produce no berries, and generates bigger and a higher number of stems (Pegiou et al. 2019). Thus, shoot quality and yield are vastly improved when selecting for male varieties. The all-male varieties used by asparagus producers are formed by the crossing of female plants with so called “supermales”. The latter is important for breeders since it carries only male sex genes and yields all-male offspring (Drost 2023).

Fig 2, Botanical overlook of Asparagus officinalis L.

The organs below the soil surface consist of an underground main stem called the crown, on which the shoot buds are located, and the fleshy roots that store energy needed for shoot growth and fern development (Drost & Wilcox-Lee 1997). Fine root hairs grown from the fleshy roots, conduct the uptake of water and nutrition from the soil (Tönnberg et al. 2018).

3.1.1 Seasonal growth and harvest in Sweden

In northern Europe, the spears are continuously harvested between spring and early summer for 8 to 12 weeks. The Swedish asparagus harvest season lasts from about the end of April in late spring, to early summer in June (around midsummer) (Tönnberg et al. 2018). Shoots are grown on the field, sometimes under plastic tunnels or with plastic soil covers to protect early- season spears from cold weather conditions. Stems are harvested by hand through cutting with knives or by breaking the spear until it snaps.

After the harvest period, emerging and remaining shoots are left on the field to develop into fully mature asparagus plants (see figure 3) that perform photosynthesis during the summer and autumn. The sugars generated from the photosynthesis are translocated as sucrose from the fern, and then accumulated mainly as the polysaccharide fructan in the underground main stem and the fleshy storage roots (Hurst et al. 1993a, Martin & Hartmann 1990). After 4-6 weeks of fern development and further 12 weeks of active accumulation of carbohydrates to the storage organs, the fern wilts and the asparagus enters a period of bud dormancy (Tönnberg et al, 2018).

The wilting of the ferns occurs during fall or early winter depending on how long favourable temperatures prevail.
The buds located on the underground stem are dormant until springtime when temperatures rise, and the harvest season is initiated when the first shoots have reached an adequate height. Asparagus shoots harvested in spring acquire the nutrition needed for growth from the carbohydrate reserves generated by the fern during the previous year of vegetative growth (King et al. 1988). This implies that the fern growth and assimilation of energy during summer and fall are determinate for the yield and quality for the next year’s harvest (Drost & Wilcox Lee 1997, Hurst et al. 1993b).

Fig. 3. Developing asparagus stems with emerging foliage.
(Image by Jürgen Treiber 2018, used with licenced permission from Pixabay)

3.2 Concerning the quality of green asparagus

3.2.1 Asparagus quality standards in the EU and Sweden

What quality attributes should producers strive for? Asparagus producers within the European Union (EU) must uphold certain marketing standards for their produce to guarantee food safety and acceptability for the consumer. Asparagus producers and exporters to Sweden and remaining EU are permitted to sell their produce under either the general marketing standards published by EU, or the standards issued by the UN/ECE (United Nations Economic Commission for Europe).

According to UN/ECE standards, green asparagus can be divided into three classes that represent different quality standards which reflect the prices that a producer may set for the commodity (UNECE 2023).

Extra class partly includes asparagus of the highest quality with completely green straight spears and perfect tender texture. Spears of lower quality are graded into Class I or II, allowing quality defects to a certain extent. Short spears are defined as those between 12- 17 cm, and long spears of above 17 cm. The minimum diameter for green asparagus is 3 mm (UNECE 2023), but such thin spears are considered unsalable according to Siomos (2018).

Meanwhile, the minimum marketing requirements for asparagus according to the UN/ECE grading standards state among other things, that spears must be intact, fresh, clean and practically unbruised. Some deterioration are allowed due to normal aging and shoots are permitted to be slightly cracked. Furthermore split, broken or hollow spears are not permitted to be marketed (UNECE 2023).

3.2.2 Quality standards according to literature

The scientific literature concerning asparagus quality provides a broader and more detailed definition of asparagus quality than presented by the marketing standards. Here, texture is one of the main quality attributes that are discussed, because the spear has a habit of developing a tough and woody feeling, especially in the basal parts of the shoots, rendering the vegetable unacceptable for consumption (Lipton 1990). These textural defects are the cause of both natural processes occurring during maturity of shoot, but also occur as a stress response from harvesting, and as an effect of storage in suboptimal conditions (Bhowmik & Matsui 2003).

Other quality attributes assessed in the literature are visual deterioration (see figure 4) and overall shelf life which is defined as storage under marketing conditions before the produce is rendered unsalable. Such quality characteristics include loss of green color and brightness, tip rot, weight loss, wrinkling and wilting, tip compactness, stem collapse, thickness and length, flavor, aroma and nutritional content (Park 2016, Palma et al. 2015, Albanese et al. 2007, Hurst et al. 1993a, Brovelli et al. 1998, King et al. 1990, Lill 1980, Siomos 2018, Anastasiadi et al. 2020). As will be demonstrated in the following sections, quality characteristics are affected by conditions and events prevailing before and after harvest.

Fig, 4. Asparagus shoots with different stages of deterioration (Matilda Travesset 2023).

3.3 Preharvest factors affecting quality

3.3.1 Physiological and anatomical factors

The quality of asparagus spears can partly be attributed to the nature of the shoot itself. Characteristics such as spear section, maturity, and spear size at harvest (defined as diameter, length, and weight), can have a significant impact on asparagus quality affecting texture, colour, storage, and shelf life.

3.3.1.1 **The concept of texture- an introduction**

Asparagus texture is experienced through the chewing and disintegration of the shoot in the mouth and is one of the most important quality attributes of the spears according to consumers (Bhowmik et al. 2000). This can be described with words as chewiness, brittleness, softness, hardness, etc. Additionally, shape and size of the foodstuff as well as moisture content and fat are also important parameters determining texture (Jackman & Stanley 1995, Waldron et al. 2003). Shoots are expected to be tender and crispy, but especially the lower parts of the spear tend to become undesirably tough and chewy, a phenomenon that can be partly credited to the physiology of the crop itself (Waldron & Selvendran 1990). Here, the textural features of the stalk are largely attributed to the characteristics of the cells and tissues that comprise it.

3.3.1.2 **ASPARAGUS STEM ANATOMY**

3.3.1.2.1 Cross section

The asparagus shoot consists of various tissues and cell types with different functions (Lill et al. 1990, Lipton 1990).

The outer parts of the stem hold the (dermal) epidermal and subepidermal layers (see figure 5) where concentrations of the green pigment chlorophyll are highest (Rodriguez- Arcos 2002). Here, tissues consist of epidermal, parenchyma, collenchyma and sclerenchyma cells (Begum et al. 2017, Hernández-Rivera et al. 1992,).

Cells within the **parenchyma** are thin-walled, contain no lignin and are highly active, conducting various metabolic processes such as photosynthesis and respiration (Raven et al. 2003), Rodriguez- Arcos 2002, Waldron et al. 2003). Meanwhile, **collenchyma** tissue offers mechanical support for immature asparagus stems. The **sclerenchyma** has a supportive function containing specialised cells called fibres and sclereids, which in turn are highly elongated cells with secondary cell walls which are often dead at maturity and provides stability to the plant (Kays, 1991).

The inner part of the stem consists of the ground tissue made up of parenchymatic cells. Scattered around the ground tissue lies the **vascular bundles** which include the xylem and phloem (Rodriguez- Arcos 2002). These tissues conduct transport of water, nutrients and chemical compounds along the stem to leaves and roots and are made of specialized elongated tubelike cells (Raven et al. 2003). Both a primary and secondary cell wall are included in cells of the xylem tissue, which are dead at maturity. On the other hand, cell types of the Phloem are living and only includes a primary cell wall (Raven et al. 2003).

A thick layer of sclerenchyma cells called the sclerenchyma sheath, surrounds the ground tissue area (Waldron & Selvendran 1990, Rodriguez et al. 2004).

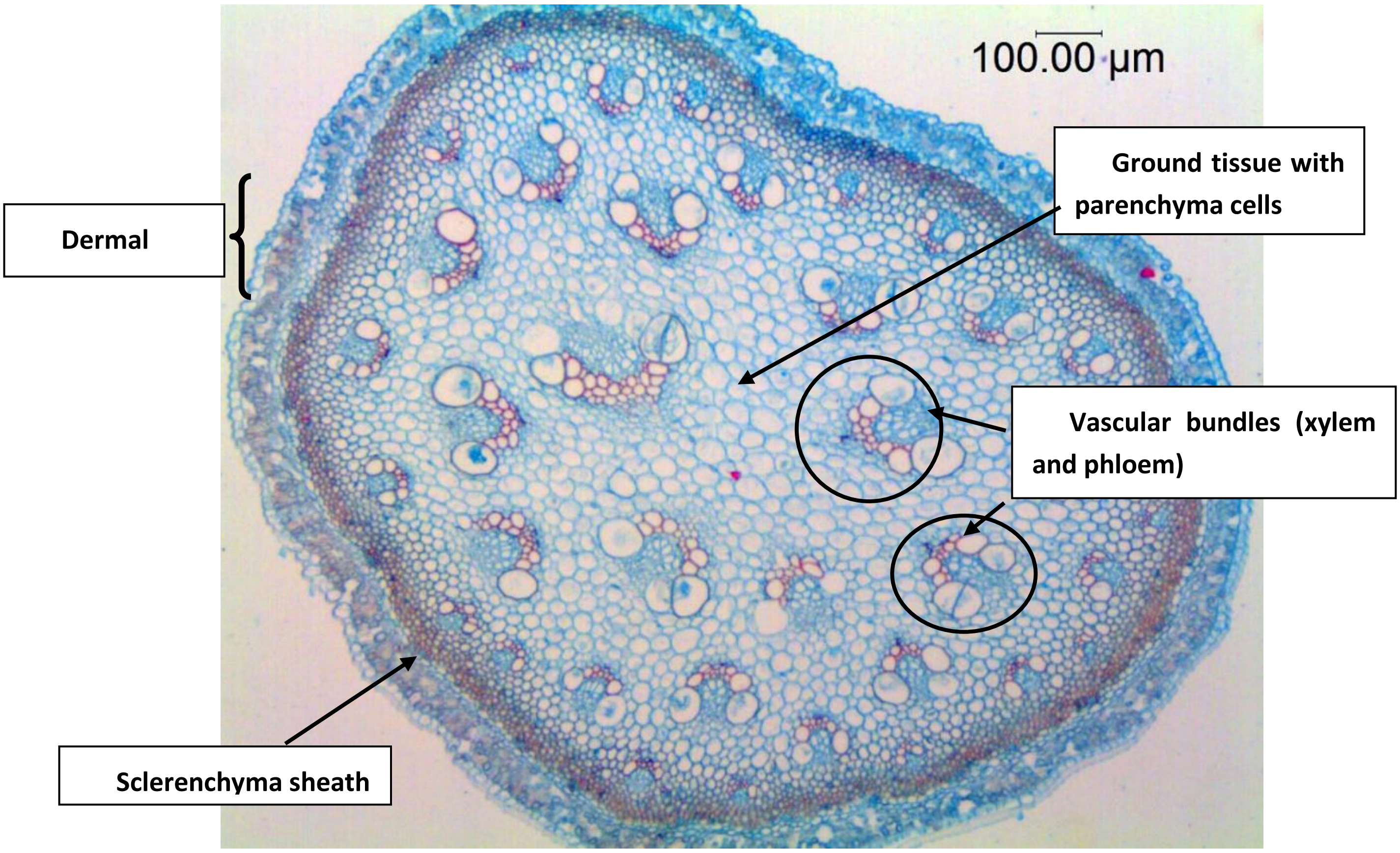

Fig. 5, Cross section of an asparagus stem showing indicators for dermal layers (epidermis and subepidermal layers), sclerenchyma sheath, ground tissue and vascular bundles. Photo: Mihai Costea (2012)used with permission).

3.3.1.2.2 Vertical stem sections

The asparagus shoot can be divided in three distinct sections that differentiate in their level of maturity and characteristics of cells and tissues.

The top section includes mainly the asparagus head and contains meristematic cells that undergo active division which gives rise to new tissues and further upward growth of the asparagus shoot (Lill et al. 1990, Lipton 1990). Due to the ongoing cell divisions, the tip section is the most metabolically active part of the asparagus spear, with the highest respiration rate (Bhowmik & Matsui 2003, Hurst et al. 1993a). Upper parts of the asparagus stalks have a higher content of the green pigment chlorophyll, as compared to the lower section, rendering it more colourful (Gantner et al. 2020).

The top section is followed by a middle section of cells that have ceased division, but instead undergo cell elongation by the establishment and swelling of vacuoles (Lill et al. 1990). This enlargement of vacuoles further contributes to an increase in the asparagus spear height (Raven et al. 2003).

The third zone consists of the bottom section of the asparagus shoot which holds both mature and dead cells that already have completed the elongation phase (Lill et al. 1990). The cells of this zone carry thick secondary cell walls that contain high concentrations of lignin and fibres (Waldron & Selvendran 1990, Hurst et al. 1993b). Lignin is an organic plant compound consisting of smaller units of cross-linked phenolic compounds providing extra stability and strength to primary and secondary cell walls within a variety of different cell types and tissues (Liu & Jiang 2006, Raven et al. 2003).

Tissues in the vascular bundles (the xylem and phloem) contain thick- walled and lignified cells, especially in the bottom section of the asparagus stalk (Chang 1983).

3.3.1.2.3 Stem anatomy affecting asparagus shoot texture- Effect of lignin and fibre on spear texture

Cell wall composition significantly affects spear texture, and especially the presence or absence of lignin, fibre and secondary cell walls, since these features contribute to the woodiness and tough feeling in the mouth (Albanese et al. 2007, Waldron et al. 2003). Furthermore, the different tissues (parenchyma, collenchyma, sclerenchyma) along the stalk contains varying proportions of immature or thick mature cells that affects the texture between the asparagus sections (Waldron & Selvendran 1990, Lipton 1990).

The middle and upper parts of the asparagus spear naturally have a more tender and brittle texture because most tissue cells are still alive or immature, containing only a phospholipidic cell membrane or additionally, a primary cell wall. The primary cell wall is made of compounds like polysaccharides, cellulose and pectin that does provide a crispy but soft texture. Here, the contents of lignin and fibres in the spear tissues like collenchyma and sclerenchyma, are significantly lower than compared to the basal parts (Villanueva et al. 2005, Raven 2003, Rodriguez et al. 2004).

In contrast, the lower more mature parts of the asparagus shoot are well known to be considerably tough. Toughness of the spear can be measured as the resistance to shearing, pressure, or cutting, thus offering a degree of resist to chewing (Bhowmik et al. 2000, Rodriguez et al. 2004). This natural toughness of the spear is necessary because the shoot needs a strong base that can eventually support the foliage as the asparagus plant matures but is not desirable for a consumer perspective (Haard et al. 1974). Synthesis of secondary cell walls occurs after the cell has concluded its growth, and since the basal sections of the spear contains more mature tissue, cells in these parts are sturdy and hard, further contributing to the toughness of the asparagus butt (Lipton 1990, Rodriguez et al. 2004).

Enhanced lignin and fibre concentrations are the main contributors to the perceived textural toughness of the basal stem parts (Hernández-Rivera et al. 1992, Lipton 1990). One of the key enzymes for lignin synthesis is the phenylalanine ammonia lyase (PAL). This enzyme is responsible for one of the initiative steps in lignin production and is significantly more active at the lower sections (Lipton 1990, Liu & Jiang 2006).

In terms of acceptable fibre content, Lipton (1990) suggests a maximum fibre concentration of 0,25 % and below. In contrast according to Poll (1993), skin fibre concentration is a better indication for edibility rather than total fibre content or lignin concentration and suggests that a skin fibre content of 0.25% is unacceptable for consumers. For reference, Shewfelt & Mohr (1960) found that the total fibre content of the asparagus butt section could reach up to 0,35%, while the middle section only reached up to 0,04%.

At the basal parts, tissues hold dead or alive cells with secondary cell walls reinforced with fibres and lignin. For instance, lignification, which is the term of lignin deposition, occurs naturally in the fibre cell walls of sclerenchyma tissue located in the vascular bundles (Kays 1991, Lipton 1990). The fibres of the vascular bundles are thick walled and lignified at the base, and thin walled and devoid of lignin at the tip. (Hernández-Rivera et al. 1992, Lipton 1990).

Additionally, the specialized tube-like cells of the vascular xylem tissue, increase in number toward the stem butt, and since these cells have a lignified secondary wall, the accumulation of xylem cells adds more textural resistance to the asparagus shoot (Brovelli et al. 1998). Moreover, the sclerenchyma sheath tissue in the basal spear parts is thicker and the cell walls are lignified unlike the upper sections of the stem (Waldron & Selvendran 1990). From a cross- sectional perspective, cell walls of tissues situated on the outer dermal layers (epidermal and subepidermal) of the spear are in general more lignified than cell walls of inner tissues (Rodriguez- Arcos 2002).

3.3.1.3 **HARVESTED SPEAR LENGTH AND DIAMETER AFFECTING QUALITY**

3.3.1.3.1 Shoot length influencing spear texture

Harvested asparagus shoot length highly influences the texture by affecting fiber concentrations. Here, the proportions of fiber rich tissues rise as spear height increases. Lipton (1990) compared fiber content of different spear lengths of same diameter. He demonstrated that shorter (50-100 mm) stems had a fiber content of 0,02% compared to 0,26% of 200-250 mm stems, concluding that taller spear were less edible since they can surpass the max recommended fiber content of 0.25% set by Lipton (1990).

Likewise, decreased spear length according to Shewfelt and Mohr (1960), improves consumer acceptance of asparagus texture. According to the authors, taller spears contain a higher concentration of fibers and water (Shewfelt and

Mohr 1960). Here spears of 20-25 cm had a total fibre content of 0.26 %, compared to 0.12 % of 12-17 cm spears, thus also exceeding the recommended asparagus fibre content. While increasing water content contributes to more tender spears, the high fiber content in taller shoots makes them still less preferable than shorter stems.

3.3.1.3.2 Spear length influencing shelf life as measured by tip rot occurrence and sugar concentrations

Shoot length at harvest seems to affect the severance of tip rot, and subsequently, the shelf life of asparagus. Lill & Borst (2001) investigated spears of different heights (50-250 mm) and concluded that proportions of the shoot tip are greater in taller shoots. A greater proportion of the highly metabolically active shoot tip resulted in reduced shelf life at room temperature, since the produce requires more food reserves to sustain cell division and other important processes. Tip rot was consequently more common among taller shoots, and shelf life was 1.5 days less with 250 mm spears as compared to 150 mm (Lill & Borst 2001). The higher metabolic rate speeded deterioration of buds and bracts located at the top parts, resulting in leakage of cell components that function as easily accessible food for different microorganisms that eventually causes the tip to rot (Lill & Borst 2001).

Moreover, carbohydrate concentration (sucrose, fructose, and glucose) decreases as shoot height increases, especially in the tip (Hurst et al. 1993a, Shewfelt and Mohr 1960). For example, 100 mm long spear had 29% more carbohydrates content than 200 mm shoots (Lill & Borst 2001).

Here, rate of spear elongation (growth rate) increases with rising spear heigh and therefore speeding up metabolic respiration. This ultimately reduces days of shelf life since available sugars used for energy conversion during respiration is depleted, leading to spear decay (Lill 1990, Lill & Borst 2001).

3.3.1.3.3 Spear diameter affecting texture

There is evidence that consumer acceptability of asparagus texture tends to be higher as stem thickness (diameter) increases, because such stalks are more tender than thinner shoots (Lipton 1990, Siomos 2018). This phenomenon is partly due to the fact that stems of equal height but different diameters, grown under same conditions, contain the same amount of lignin and fibers in the xylem vessels. Therefore, thinner spears will have a higher concentration of fibers and lignin in relation to their volume compared to thicker shoots (Lipton 1990).

This difference appears to be more noticeable near the lower stem section since the amount of fiber rich xylem tissue is higher (Brovelli et al. 1998, Lipton 1990).

Drake et al. (1979) measured asparagus texture by determining the force required to cut through the spear at different sections along the stem. Likewise, it was concluded that spears of less diameter (1-1.6 cm) indeed possessed higher toughness as well as percentage moisture content compared to thicker spears (1.6-2.2 cm).

However, when stems were processed by blanching for a few minutes, the thinner spears were less tough compared to the thicker samples (Drake et al. 1979). Moisture also contributes to texture by adding tenderness. Surface area to volume ratio of thin spears is greater compared to thicker and bigger spears. This means that the smaller asparagus have a higher surface area but lower volume. Thus, water can easily evaporate from the spear to the atmosphere, thereby causing moisture loss (Anastasiadi et al. 2020). For example, moisture loss for thin spears (12-13.9 mm) was 6.2%, and 3.3% for thick shoots (17-20 mm) under a modified atmosphere storage at 7 C for 17 days (Anastasiadi et al. 2020). According to Gantner et al. (2020), a weight loss of 8% and above is more noticeable for the consumer, where the spear quality start to become less acceptable, and water loss is the main cause of spear weight loss in asparagus spears (Shalaby et al. 2014). Although Hurst et al. (1993b) added that the limit could be extended to 10-15 % water loss before considered unacceptable. Maintaining moisture levels is therefore important to uphold acceptable texture, and harvesting thicker spears might be a good practise to prolong this quality.

3.3.2 Agronomical factors

3.3.2.1 **Plant age during production**

There is a strong correlation between fern growth the previous season and spear quality of the subsequent harvest season. As stated earlier, the plant needs about 4.5 months for development of foliage and photosynthesis after the harvest period to replenish its carbohydrate status in the storage roots (Tönnberg et al. 2018, Lipton 1990). But fern development and carbohydrate build-up to the roots needs more time as the asparagus plant ages, hence production season which normally extends to between 8 to 12 weeks in northern Europe, needs to be gradually shortened with time (Drost 2020, Paschold et al. 2001).

An insufficient carbohydrate concentration in the roots during the harvest season, results in lower yield and thinner spears, even if the stems emerge from larger buds, which would typically produce thick spears if enough energy reserves were available (Bhowmik et al. 2002, Drost & Wilcox Lee 1997, Paschold et al. 2001).

3.3.2.2 **Plant depth and density**

Plant density and crown depth can have an impact on shoot weight and diameter (McCormick & Thomsen 1989, González & del Pozo 2001). McCormick & Thomsen (1989) saw a reduction in spear weight as the crown depth (relative to the soil surface) decreased, while harvested spear number (overall yield) increased. An increased depth of 100 to 300 mm (relative to the soil surface) increased spear weight by 20 % while decreasing mean spear number by 20%. Gonzáles & del Ponzo (2001) found a higher yield of thicker spears as the crown depth increased from 10 cm to 30 cm. They emphasized that planting crowns at 30 cm depth was not beneficial since this prolonged spear emergence (at which the stem penetrates the soil surface) and produced a higher number of spears above 17 mm in diameter, which is not desirable for asparagus designated for the export market.

Moreover, density or number of asparagus crowns planted per unit of area can also affect yield and spear thickness (Siomos 2018). Increasing plant density from 19000- 44000 crowns per hectare, enhanced shoot numbers from 180.000 to 250.000 /ha but reduced mean spear weight from 22.1g- 20.3g. Although González & del Pozo (2001) found no significant difference of spear yield and quality when number of plants ranged between 22.000-33.000/ ha.

3.3.3 Environmental factors

3.3.3.1 **Harvest date and growth temperature**

3.3.3.1.1 Temperature and harvest date affecting textural quality

Asparagus texture appears to be affected by growing air temperatures on the field. Brovelli et al. (1998) demonstrated that tips from stems harvested in early spring where the mean temperature was 15.1 C, had the same textural toughness as the middle section from stems harvested during the summer (mean temperature 24.3 C). It was concluded that the cold production temperatures decrease stem growth and elongation. Here, temperatures affect spear elongation more than fibre development and lignin deposition. Hence, a lower growth rate presiding under cooler weather, results in a higher concentration of fibres in relation to volume compared to fast growing spears grown under warm temperatures (Brovelli et al. 1998, Anastasiadi et al. 2020).

Likewise, Poll (1993) investigated spear skin fibre content and concluded that growth temperature along with shoot diameter have a significant impact on fibre concentration. Stems of equal harvest height (22cm) grown under cool temperatures of 10.2 C had twice as much skin fibre, or three times as much, compared to a growing temperature of 14 C and 20 C respectively. Again, diameter was also an important factor in texture acceptability. Stems with a diameter lower than 16 mm developed under a mean temperature below 14 C, exceeded the acceptable skin fibre percentage of 0.25%. Interestingly, thicker spears (16-20 mm diameter) grown under cooler temperatures (14 and below) were not equally affected, since they had a lower proportion of skin fibre content compared to thinner spears.

Similar conclusion was drawn from other experiments which demonstrated an increase in textural toughness of spears harvested during a period of cooler weather (Bhowmik et. al 2002, Lipton 1990).

3.3.3.1.2 Temperature and harvest date affecting shelf life as a function of visual quality

There is evidence that shelf life of asparagus collected during early production season is higher compared to late harvested shoots. Here, air temperature directly affects spear temperature, which increases as the harvest season progresses (Lill & Borst 2001). When cooler temperatures prevail during spring harvest, spears will have a lower inner temperature compared to shoots collected in the summer. This results in a lower metabolic activity for cooler spears which has a positive impact on shelf life when harvested, as well as decreasing the onset of tip rot (Lill & Borst 2001, Hurst et al. 1993b).

Moreover, higher temperatures during growth will initiate spear tip feathering (see figure 6) by stimulating an early onset of tip bract opening, an undesirable quality defect (Hurst et al. 1993b, Siomos 2018).

Fig. 6, Asparagus spear tips with different stages of feathering. The left shoot has a compact and tight tip compared to the two stems on the right. (Matilda Travesset 2024)

3.3.3.1.3 Harvest date and temperature affecting shelf life as a function of sugar content and rate of metabolism

Asparagus carbohydrates constitute the main building blocks of the asparagus stem. Sugar is the primary building block for asparagus spear to sustain normal metabolism (Lipton, 1990)
Concentration of sugars in harvested spears is affected by temperatures during the harvest season and the amount of food stored in the roots that can provide the shoot with carbohydrates (Bhowmik et al. 2001). As will be demonstrated, temperature and carbohydrate reserves are closely related to harvest date (Lipton 1990, Bhowmik et al. 2002). Moreover, storage time and shelf life are highly correlated to spear food reserves and respiration rate prevailing at harvest (Hurst et al. 1993a).

Shoots collected towards the end of the harvest season will have significantly less sugar content compared to early season spears, due to depleted carbohydrate root reserves to sustain shoot growth (Bhowmik et al. 2002, Zurawicz et al. 2008, Lill & Borst 2001).
For example, sugar content in the shoot can fall to 50% during the harvest season (Lipton 1990). Also, higher temperatures during summer harvest season will enhance elongation and respiration rate of spears. This will increase the demand for carbohydrates from the already depleted root reserves, further decreasing the total amount of sugars in the spear (Anastasiadi et al. 2020, Hurst et al. 1993a).

Lower energy reserves in the form of sugars of harvested stems results in a reduced ability to maintain normal metabolism (Bhowmik et al. 2002). Moreover, spears will experience a higher rate of metabolism if hot temperatures prevail during time of harvest. Both conditions will decrease the storage time and shelf life of the produce by up to several days (Bhowmik et al. 2002, Lill & Borst 2001). For example, Hurst et al. (1993b) detected a reduction of 2,5 days in shelf life, during a harvest season of 12 weeks. According to Lill & Borst (2001), higher carbohydrate measured in tips of early spears will provide more energy for detached shoots to maintain normal metabolism and so prolongs marketable quality.

3.3.3.1.4 *Harvest date and temperature affecting shelf life as a function of spear size.*

Shelf life is also associated with spear size and thickness (see figure). Thicker spears have a higher sugar concentration and are less affected by moisture loss (Anastasiadi et al. 2020, Hurst et al. 1993a).

The diameter (thickness) of harvested spears is partly affected by harvest date and pure physiological factors of the asparagus plant. The asparagus crown harbours a cluster of buds from which the shoots will develop. A growing stem on one cluster often supresses the emergence of additional spear from buds on the same cluster, until the initial stem is harvested or finished growing (Drost & Wilcox Lee 1997).

At the start of a growing season, the first emerging shoots on a cluster arises from the bigger dominant basal buds on the crown, therefore producing thicker spears at the beginning of the harvest season. As time progresses the smaller buds near the surface emerge.
But buds of equal size from separate crowns and plants are not necessarily activated simultaneously. Therefore, thinner spears from smaller buds closer to the surface will also emerge early in the season but from crowns whose larger buds have already been spent. This means that the total production of thicker spears will be greater at the beginning of the production season, but the emergence of thinner spears will yet occur (Woolley et al. 2008, Drost & Wilcox Lee 1997, Siomos 2018).
In contrast, Hurst et al. (1993b) claims that the smaller buds on the crown near the surface emerge first, producing thinner spears at the very early stages of the harvest season. Eventually the thicker spears will appear, to then decline again as the season progresses. However there seems to be a clear pattern where the majority of larger and thicker shoots are produced during early harvest season.

Spear size at harvest date is also related to the depletion of carbohydrate resources that occurs during time. Asparagus plants with reduced food supplies in the roots at the end of the season will ultimately produce smaller and thinner spears (Hurst et al. 1993a, Anastasiadi et al. 2020).

Moreover, prevailing growth temperatures also affect spear diameter. As the production of spears numbers increased rapidly with rising mean temperatures, root reserves are depleted which reduces the diameter and weight of the emerging spears (McCormick & Geddes 1993, Zurawicz et al 2008). However, too cold temperatures can impede spear growth and development, also producing thinner spears (Hurst et al. 1993b).

Meanwhile, increasing temperatures observed during the summer season can decrease fresh weight by enhancing stem elongation that exceeds the synthesis of dry matter. This will eventually produce taller but thinner spears (McCormick & Geddes 1993).

Hurst et al. (1993b) found that harvest date had a significant impact on spear weight which in turn affected shelf life (storage at 20 C). Spears emerging in early spring had a shelf life of 6 days compared to 3.5 days for late season spears (over a 12- week period) before the produce became unmarketable (by showing signs of wilting and stem collapse). Thinn spears which have a greater surface area and less volume (compared to thicker shoots), are more exposed to weight reduction by water loss through transpiration (Hurst et al. 1993b).

Similarly, spears collected during the first weeks at harvest season had lower weight reduction during shelf life due to lower moisture loss, compared to shoots harvested at the end of the season (Anastasiadi et al. 2020). According to Anastasiadi et al. (2020), spears of the smaller diameter lost 6.2% water as compared to 3.3% for thicker shoots. Additionally, thicker spears have a higher sugar content, which contributes to the longer shelf life (Anastasiadi et al. 2020, Zurawicz et al. 2008).

3.3.3.1.5 Harvest date and temperature affecting sensitivity to postharvest cold storage

Field temperature as influenced by harvest date has a significant impact on the severity of chilling injury in asparagus stalks stored at 0-2.5 C. Chilling injury causes discoloration and reduction of tip quality, and this can be more severe as the harvest season progresses. For example, early harvested spears did not show any signs of chilling injury until 4 weeks of storage at 1.5 C, whereas late harvest stalks were already afflicted by this phenomenon after 1 week (Klieber & Wills 1992). Higher growing temperatures prevailing later in the season make the spears more sensitive to low storage temperatures. Reduced sugar content within late season shoots, due to depleted carbohydrate reserves in roots, and increased growth rate, also renders the spears more vulnerable to cold temperatures during storage (Klieber & Wills 1992).

3.3.3.2 **Impact of water availability on spear quality**

Soil water availability throughout summer/fall fern growth and bud development, affects the size and thickness of spears emerging during the next harvest season (Drost & Wilcox-Lee 1997, Drost 1999). The asparagus plant has a relatively low water requirement especially during stem growth (Rolbiecki et al. 2024) and needs a well-drained soil for optimal growth (Carter et al. 1988).

However, sufficient access to soil water during stem growth and elongation just before harvest are important to maintain optimal water concentrations of the harvested edible spear (Shewfelt and Mohr 1960). This is vital since healthy moisture levels will add to spear weight, improve textural tenderness, and increase days of shelf life at the market.

Moreover, insufficient access to water during fern growth occurring after the harvest season, disturbs development of the foliage and decreases the capability of the plant to develop a healthy canopy for photosynthesis. This results in a reduced production of carbohydrates for bud development (Drost & Wilcox-Lee 1997, McCormick & Geddes 1993). Carbohydrate food depletion causes smaller sized buds, thus increasing the emergence of thinner and smaller spears during the upcoming harvest season (Drost & Wilcox-Lee 1997).

4. Discussion

The aim of this literature study was to identify preharvest factors and how they affect the quality of green asparagus after harvest.

Concerning **asparagus physiology** which highly affects textural quality; it was clear that asparagus shoots have a tougher texture towards the base due to higher lignin and fibre content residing in various tissues at that location. The spear tips on the other hand were tender, less fibrous due to young cells with high metabolic rate undergoing cell division, consisting only of primary cell walls. From a cross-sectional view, the cells of the dermal tissue were generally more lignified and fibrous than the innermost tissues.

Spear diameter and length at harvest seemed to have a significant effect on quality as well such as shelf life after harvest. Shorter but thicker spears seemed to be more desirable form a consumer perspective according to literature.
The occurrence of tip rot was associated with taller spears, shortening shelf life up to 1,5 days. These shoots have a higher proportion of metabolic active tips, and a higher rate of spear elongation, thus accelerating the depletion of sugar reserves needed to maintain respiration and metabolic activity. Moreover, the concentration of fibre increased with spear length, where the accepted maximum fibre content (0.25%) could be exceeded among taller spears. This was slightly unexpected, as the higher proportion of spear tips in taller spears should in theory contribute to a more tender texture since this shoot section is less lignified and fibrous.

Apt thickness was also desirable in harvested spears. Fibre to volume ration increases with decreasing shoot diameter, rendering thinner spears more though. Moisture loss was also more prominent with water evaporating faster as the diameter declined, contributing to weight loss and reduced tenderness. Thickness was also related to higher sugar content, hence delaying shoot wilting and decomposition by storing more energy for metabolism, resulting in longer shelf-life. Interestingly, contradictory to most literature, there is a market for thinner spears and there seems to exist a division between consumers that either prefer fat or thin spears. It appears that method of cooking also influences the final textural feeling (Bittman. 2006, Drake et al. 1979), and skinny shoots seems to be more preferred among chefs, Darnton, 2013). It is unclear however where the line is drawn between what is considered thick or thin. Likewise, spear height at harvest significantly affects fibre content which means that thin but tall spears could still be undesirable for consumers preferring skinny shoots. Short spears range from 12-17 cm according to UN/ECE marketing standards, but combined with shoot diameter, it is unclear where this line is drawn between acceptable vs. undesirable from a consumer perspective.

Not much could be concluded about **agronomical factors**, however, aspects such as nutritional requirements and different soil types were not included. As asparagus plants ages, more recovery time is needed for fern growth and carbohydrate accumulation for the following season. Low carbohydrates concentration in the roots will reduce spear thickness, producing thinner spears with higher spear toughness and shelf life as a consequence.

Furthermore, it was indicated that plant depth and density may need to be balanced to produce high quality spears while attaining an adequate harvest yield. Crowns (roots) established deeper in the soil would increase spear diameter, however while lowering the number harvested shoots. Meanwhile, crowns planted closer to the surface had an opposite effect. Increasing plant numbers per surface area would also increase overall yield, with the cost of producing thinner spears. However, this contrast was not evident at all plant densities.

Environmental factors were frequently covered in the literature and seems to have a significant influence on asparagus spear quality.

Especially prevailing temperature at harvest and during growth season had a hight impact.

Low temperatures (under 14 C) during growth season would affect spear texture by slowing down cell elongation and growth, while fibre content remained the same in relation to fast growing shoots. Hence, the concentration of fibre to spear volume is higher in slow growing asparagus, adding more toughness to the texture. But undesirable effect of cold weather on shoot texture would diminish with increasing spear thickness because thinner spears seem to become a problem when shoots are grown below a certain temperature. Hence, thin spears grown under warm conditions might not be a problem from a consumer perspective, which could partly explain the disagreement whether thick or thin shoots are the most preferable kind.

Moreover, cooler growth temperatures increased resistance against post-harvest chilling injury for asparagus stored down to 0 C. It also improved post- harvest shelf life as a function of tip rot, due to lower metabolism in cold growing shoots.

On the other side, warm weather conditions during growth also affected spear quality in several ways. It was evident that spear elongation and metabolic rate accelerated as growth temperatures increased. This would produce taller, but thinner spears as speeded elongation would outrun the production of fresh weight. Hot weather conditions would also deplete root sugar reserves due to higher need for metabolites for respiration as temperatures increases, while stimulating asparagus tip feathering as a consequence of bract opening.

Shoot quality was also dependent on date of harvest. Carbohydrate reserves in asparagus roots would deplete as the harvest season prolonged, leaving late season shoots with lower concentrations of sugar needed for respiration, and hence reducing shelf -life. Spear diameter was also reduced as the season progressed due to thicker stalks stemming from the larger dominant buds, which emerged at the start of the harvest period.

Water conditions on the filed were most important during fern growth and photosynthesis for root carbohydrate accumulation needed for next harvest season. Meanwhile spear moisture content which contributes to textural tenderness, added weight and shelf-life is also dependent on soil water availability, but the requirement is not as profound as during fern growth.

4.1 Possible implications of climate change on future asparagus spear quality in Sweden

The overall question here is if producers would experience increased quality effects, rendering less spears suitable for consummation. An unpredictable climate would require producers to be more dynamic and adaptable to handle weather changes.

Weather patterns such as increased precipitation during springtime and autumn, along with dry summers are expected from a Swedish perspective (WFF 2024, Naturskyddsföreningen 2021). Moreover, early springs and warmer temperatures during fall are also a possible permanent outcome for the future.

A premature onset of spring could shift the harvest season to an earlier start because bud emergence is initiated once soil temperature reaches a certain point. However, the question is if this would prolong the overall harvest season from the current 8 to 12 weeks, or if the season needs an earlier break for fern growth and root carbohydrate buildup. A prolonged warm autumn season with adequate precipitation could be beneficial for fern growth, hence enabling a longer harvest season where photosynthesis and carbohydrate accumulation are postponed to late summer and fall. Although, possible expansion of harvest season is just speculative and might not be possible if future weather pattern during fall time means heavy rains and consequently waterlogged soils, which will negatively impact harvest and asparagus plant recovery. Hence, the possible consequence of climate change might be shorter seasons or just a shift to an earlier harvest. A prolonged harvest season would increase total yield, but spear quality could be compromised in shoots harvested later in the season if sugars reserves are depleted, leading to thinner spears of shorter shelf-life.

Warm springs combined with hot summers could potentially alter the quality of harvested spears in different ways. Taller but thinner spears could be more plentiful due to increased seasonal growth temperatures which accelerates elongation but decreases sugar content in the shoot by faster depletion of carbohydrate storage in roots. Subsequently, this would impact shelf-life by increasing respiration rate and water loss in harvested spears, thus initiating the onset of tip-rot and early wilting. Hot and dry summers would also decrease the quality of shoot tips by impacting the number of harvested shoots with undesirable feathered tips. Consistent monitoring of spear quality on the field and harvesting more frequently, might become a necessary solution to prevent lanky shoots of poor quality and feathery tips.

Another possible consequence would be the reduction of spear quality and shelf life due to less moisture content, hence reducing shoot weight and textural tenderness. Irrigation of asparagus fields is still not a common practice in Sweden, but this may need to be considered to endure periods of extended drought and elevated temperatures.

At the same time, asparagus producers might need to adapt the plantation to periods of excess precipitation especially during fall. Planting crowns above ground level through ridges could be one solution as proposed by Dubon (2022). In these conditions, crown depth optimal for prevention of waterlogging needs to be balanced without compromising harvested shoot diameter which declined with reduced depth.

Future impact on shoot texture is also unclear as several factors are involved. Warm temperatures decrease the portion of fibres to volume, but this effect might be countered if the overall thickness is expected to decrease, and if the moisture content is low due to lack of precipitation.

4.2 Future aspects

This paper was mostly focused on quality attributes such as texture and spear size. Color, nutritional value, aroma, and flavour were omitted but these should be included in further studies to achieve a more holistic perspective on possible quality issues that may affect consumer acceptability. Likewise, factors which were not brought up in this paper such as soil conditions, pathogens and fertilization should also be included to get a broader perspective and a better analysis.

Moreover, genetic factors seem to have significant implications for asparagus quality. This can affect attributes such as weight, thickness, and tip compactness amongst other characteristics (Knaflewski et al. 2014, Siomos 2018), which might alter previous conclusions. The literature used to analyse preharvest factors affecting quality stems from separate experiments oftentimes using different cultivars. Hence, it would be interesting to analyse how different cultivars, commonly used among Swedish producers, influence the final quality in relation to our practices and climatic conditions.

It would also be valuable to further investigate consumer preferences concerning spear thickness and height along with harvest date and growth temperatures. This could determine how these attributes interact and whether a set limit (e.g. minimum height in relation to diameter and growth temperature) concerning each factor can be set to help producers grow high quality shoots.

Additionally, investigating post-harvest factors could be beneficial since they are equally important to the final spear quality. Finding the best combination of practices before and after harvest would be necessary to optimise asparagus quality, especially considering future challenges that climate change might bring about.

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