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DOCTORAL DISSERTATION

MSc Hicran Sadan-Ozdemir

INFLUENCE OF SUBSURFACE DRIP IRRIGATION ON THE GROWTH AND YIELDING OF ASPARAGUS IN ORGANIC SYSTEM ON THE LIGHT SOIL

FIELD: agricultural sciences
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SUPERVISOR(S) OF DOCTORAL DISSERTATION

Prof. Dr. Roman Rolbiecki
Bydgoszcz University of Science and Technology, Poland
Prof. Dr. Ferenc Pal-Fam
Hungarian University of Life Sciences, Kaposvar Campus, Hungary

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"The greatest fortune in life is the presence of someone who believes in your potential. A person who makes you feel that you can always do better, who gives you courage, and who walks with you wholeheartedly… that person is truly a gift."

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1. INTRODUCTION

Asparagus is a vegetable rich in bioactive compounds consumed in many countries of the world [Yang et al. 2022]. Mainly, asparagus is a vegetable consumed in the form of young, thickened and ready-to-consume shoots called spears. However, asparagus and its species have been and are still used extensively as a source of medicinal bioactive substances [Pegiou 2019]. Asparagus has good potential for fresh consumption in the market. However, organic crop production does not allow the use of artificial pesticides or chemical fertilizers. Alternatively, they emphasize biodiversity and cultural methods with environmentally friendly inputs. As a commercial crop, asparagus can be somewhat difficult to produce organically due to potential difficulties in managing weeds [Kuepper 1998].

Asparagus is one of the most popular vegetables consumed around the world and has been cultivated for more than 2000 years [Chen et al. 2022]. It is of great importance to choose advantageous and suitable varieties for the climate in order to obtain high efficiency in the cultivation of asparagus (*Asparagus officinalis* L.), which is a perennial vegetable. Fortunately, breeding studies are creating new asparagus varieties [Knaflewski et al. 2015].

According to FAOSTAT data for 2022, global asparagus production reached approximately 8.824 million tonnes. China leads the World in asparagus cultivation with approximately 7.684 million tons, accounting for approximately 87% of the world's total production. In Europe, Germany led asparagus production with approximately 110.000 tonnes harvested in 2022. Other significant European producers included Italy with 47.000 tonnes, France with 26.800 tonnes, and Poland with 23.800 tonnes. Poland's production marked a 31.5% increase compared to the previous year, reaching an all-time high and ranking 11th globally among asparagus-producing countries.

Challenges are different around the world, and environments vary greatly from tropical regions with harvest potential during the growing season to temperate regions with limited harvest time in the spring. Methods for production vary widely and include trunk culture, spear forcing systems, green or white spear production, and multiple harvests per year. From a genetic perspective, varieties should be broadly applicable to different climates, soils, and applications [Drost 2023].

According to the data obtained from Knaflewski [2020] study, asparagus production in Poland is increasing every year. In this increase, green asparagus mostly has a larger share in the total amount of asparagus produced. It has been observed that new plantations need to be established outside of traditional growing regions, examples of these regions can be given as Masovia, Lublin or Kuyavian-Pomeranian provinces.

Environmental factor is an important criterion in the planting method of asparagus. Therefore, in most production regions, especially those with temperate and subtropical climates, temperature is the main factor determining spear yield and asparagus quality, in addition to growth and development [Chen et al. 2022].

In asparagus, yields are generally higher in warmer regions and lower in tropical regions. This is because early spears are at risk of frost and air temperatures combined with cold soil can often slow spear formation and growth rates. The length of the harvest season in spears should be balanced with fern development. Root carbohydrate charging after harvest. However, in temperate European production regions, plastic mulches are widely used to regulate soil temperatures to increase spear productivity. High tunnels are also integrated into green production systems to encourage early spear emergence or to protect against diseases. In asparagus cultivation, other management practices can be integrated into the production system in the future to change the environment and thus change the production period and/or increase productivity [Drost 2023].

Asparagus has a very deep root structure, so its water absorption from the soil is quite high. The advantage of this is that it is more tolerant to dry air compared to other shallow-rooted crops. Deep rooting also allows for longer intervals between watering applications compared to other succulent plants. In order to achieve high yields in asparagus cultivation, irrigation in the region will be significantly needed. Apart from this, asparagus roots can grow up to 3 meters deep in well-drained soil. Most soils are acceptable if the water table does not come within 3 feets of the surface during the growing season. [Brandenberger et al. 2014]. It is important to understand the changing characteristics of water needs and the relevant determining factors within the framework of climate change for crop production and the use of agricultural water resources. Climate change has become a very important problem for scientists and governments around the world. On top of this, it has been determined that the average global temperature has been increasing since 1880, According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [Jia et al. 2021].

In recent years, the use of surface and subsurface drip irrigation in irrigation systems has increased significantly around the world. The main advantage of this system is the potential to increase crop yields while reducing water application, fertilizer and cultivation costs. The soil moisture distribution pattern around a water emitter depends on: firstly the total volume of water applied; secondly the emitter flow rate, source configuration (surface, subsurface, point or line) and initial boundary conditions; thirdly the soil physical properties and their spatial distribution; and finally plant root activity. Irrigation management also, according to El-Maloglou et al. [2010] it was found that surface and subsurface drip irrigation system can increase water use efficiency but this is only possible when the irrigation system is designed to meet the soil and plant conditions. That irrigation system is very popular in organic cultivation around the World and in Poland as well.

1.1. RESEARCH OBJECTIVES OR HYPOTHESIS

The research hypothesis assumed that the use of technology of subsurface drip irrigation in the organic cultivation of asparagus grown on green spears could contribute to the increase in the use of sandy soils and Dutch and German asparagus cultivars by achieving better production results in the organic cultivation of asparagus on this type of soil.

1.2. PURPOSE OF RESEARCH

The aim of the research was to determine the influence of subsurface drip irrigation on on the growth and yielding of asparagus in organic cultivation on the light soil.

Due to the limited literature data on organic cultivation of asparagus in irrigation conditions, the following specific aims were adopted:

- to determine the water requirements – field water consumption (S) of asparagus during the irrigation period under subsurface irrigation conditions,
- to assess the suitability of the Hargreaves model, modified by Droogers and Allen, for calculating crop evapotranspiration (ET_c),
- to determine the plant coefficients k_c for the Hargreaves model, modified by Droogers and Allen, and to determine the water requirements of asparagus in organic cultivation based on the climatic criterion (ET_{cD}),
- to estimate of the effect of subsurface drip irrigation on growth of asparagus summer stalks (height, diameter, number and weight of the summer stalks) in organic cultivation,
- to estimate the effect of subsurface drip irrigation on marketable yield of chosen asparagus cultivars grown for green spears in organic cultivation,
- to analyze the effect of subsurface drip irrigation on the quality of the spears,
- to asses the influence of subsurface drip irrigation on healthiness of summer stalks of asparagus in organic cultivation

2. LITERATURE REVIEW

2.1. ORIGIN AND HISTORY

Asparagus (*Asparagus officinalis* L.) is a vegetable whose young and thickened shoots, called spears, are consumed predominantly and has been used in the past and is still used as a source of therapeutic bioactive substances. This vegetable has been cultivated by many civilizations over the years, including the Egyptians, ancient Greeks and Romans. Its appearance as an offering depicted on an ancient Egyptian frieze is the first indication of its use, but it is not yet clear whether the plant had a food or medicinal use at the time [Pegiou et al 2020]. In addition to this, asparagus as a perennial herb, is originated from the eastern Mediterranean and Asia Minor and has been cultivated for more than 2000 years. At present, more than 60 countries around the world grow asparagus including the China, United States, Italy, Netherlands, Canada, Germany and other western developed countries. Currently, production, scientific research and development of asparagus have extended from the developed to developing countries, and China has become one of the major destinations. Peru is a one of the world's leading exporter of asparagus [Schwarz, Mathijs 2017].

It was once classified in the lily family, like the related Allium species, onions and garlic. However, genetic research places lilies, Allium, and asparagus in three separate families the Liliaceae, Amaryllidaceae, and Asparagaceae, respectively the Amaryllidaceae and Asparagaceae are grouped together in the order Asparagales. Sources differ as to the native range of *Asparagus officinalis*, but generally include most of Europe and western temperate Asia [Plants of the World Online 2018]. It has been estimated that there are 230 taxa species in the genus of asparagus plant. Among these species, the most popular and cultivated vegetable plant in the world is *Asparagus officinalis*. Thereupon, in the final infrageneric classification, asparagus is divided into three subgenera. These are; Asparagus, Myrsiphyllum and Protasparagus [Kanno Yokoyama 2011]. It is widely cultivated as a vegetable crop. Its genome has been sequenced as a model to study the evolution of sex chromosomes in plants and dioecy [Harkess et al. 2017]. Although its origin is thought to be in the Eastern Mediterranean, it also grows in Central Europe, the Caucasus and Western Asia. It was introduced centuries ago to North America, Northern Europe and parts of South America, North Africa and Australia [Pegiou et al 2019].

2.2. BOTANIC AND VARIETIES DESCRIPTION

Asparagus, a perennial flowering plant species, is colloquially known as sparrow herb, but its scientific name is Asparagus *officinalis*. Asparagus, a spring vegetable, is consumed mainly in young shoots. In the past, asparagus vegetable was classified in the Lily family, like onion and garlic, which are Allium species, but after studies, it was distributed in three different families as Liliaceae, Amaryllidaceae and Asparagaceae. Apart from this, wild asparagus cultivation is high in Europe and Temperate Asia regions [Wikipedia 2020].

There are two main forms of asparagus are:

- Wild asparagus: Wild asparagus is used and enjoyed in many different regional dishes around the world [Ghirardini et al. 2007]. In addition, the popularity of wild asparagus today is not only due to its taste and high nutritional value, but also to the motivations of society [Acosta-Naranjo et al 2020]

- Cultivated asparagus: They are those that are cultivated. They are thicker and shorter than wild asparagus.

Asparagus can be classified according to its production method and there are many varieties of asparagus to choose from with the most visibly different being the purple varieties. These are:

White and Green Asparagus: White asparagus (*Asparagus officinalis* L.) is an important and popular crop in Germany [Statistisches Bundesamt 2011]. Fresh and minimally processed white asparagus spears are highly sensitive to microbial spoilage, often accompanied by inherent changes in physiological and textural quality [Herppich 2014]. In this particular, green asparagus, which is considered a very healthy product; fresh or freshly cut, its popularity and consumption is increasing due to its structural and sensory qualities and abundant nutritional components [Nikaido et al. 2014]. Asparagus is used as both green and white shoots (spears); It is also harvested before exposure to light. It is a crop cultivated in almost every region of the world; major player regions are China, Western Europe, North America and Peru [Pegiou 2020].

While white asparagus is more popular in some countries, such as the Netherlands, Belgium and Peru, in other countries (e.g., the UK) it is generally more common in the green form in market. In addition, green asparagus is more known and consumed around the world; for that matter, some countries only see this form and consumers are unaware of the white version. This has caused some scientific studies to not even specify which type was used (so it should be assumed to be green). The most agriculturally obvious difference between the two forms is that white asparagus is harvested before the shoots reach the soil surface/light, while green asparagus is harvested after the shoots reach the soil surface/exposure to light. But botanically, both are one species, and while sometimes the same variety is used to produce both variants, producers have chosen to use the one that suits the production method [Pegiou et al 2019].

In brief, white asparagus, is grown by covering it without sunlight, so chlorophyll cannot develop in the plant and its color is white because it does not perform photosynthesis. It tastes a bit sweeter than the green asparagus and contains less fiber. At harvest time, the machines pass through the rows and cut the asparagus spear that cracks through the soil. Another harvesting method is to cover the asparagus with thick plastics wrapped in twisted iron rings, so that it can be easily harvested by removing the plastic at the time of harvest. Green asparagus; It is the type of asparagus that is the most common in the countertops. Its texture is sharp and when it is cooked, the green color shines and becomes more pronounced. According to consumers, there is a well-known perception that it is harder as thick asparagus, but this is wrong because there are fixed fibers that are not seen in thick asparagus, most American asparagus is of this varieties, which ranges from pencil-thin to very thin [Sergio et al 2019].

Purple Asparagus: *Asparagus officinalis* is known to be rich in functional components. The green spears have a small amount of anthocyanin, and the spears often take on a red tinge. Recently, asparagus with reddish purple spears has attracted consumers. Purple asparagus is expected to have a higher antioxidant activity than the green or white varieties, because of the increased levels of its abundant anthocyanins [Sakaguchi et al.2008].

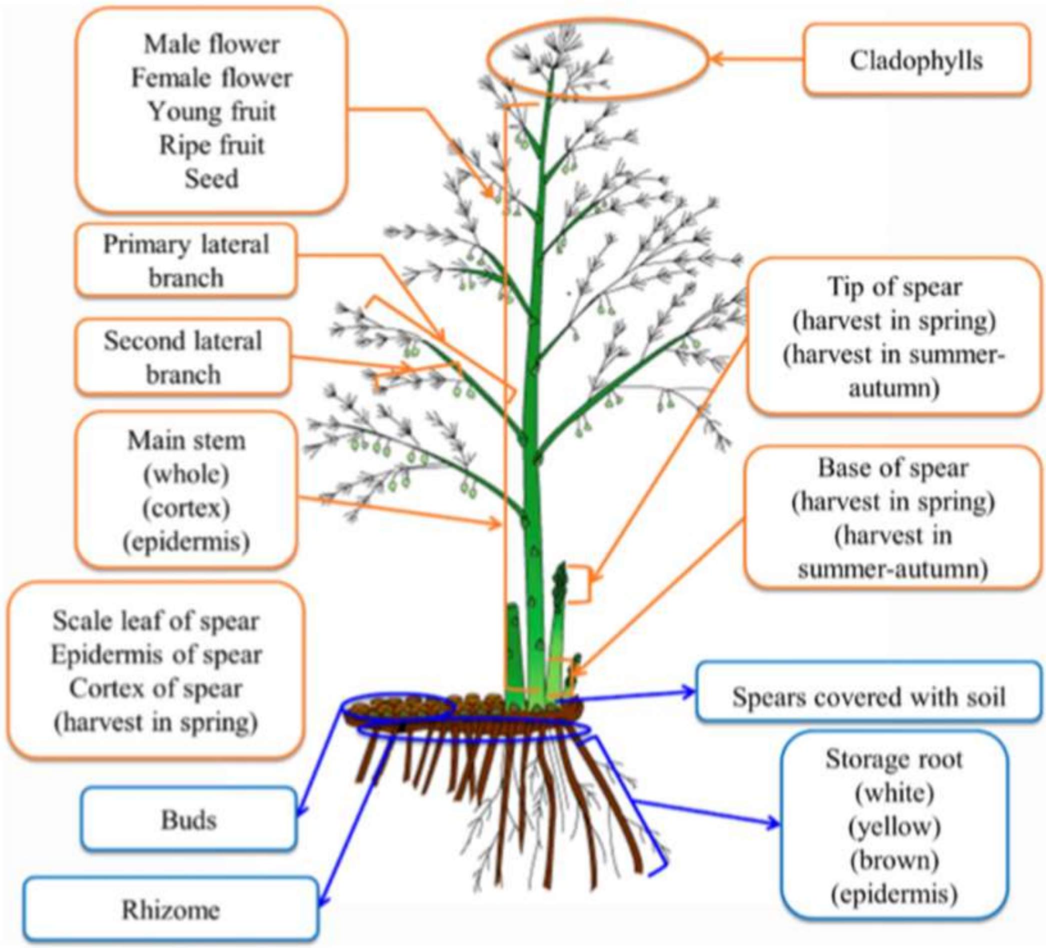

Fig. 1. Sampling parts of asparagus [Motoki et al. 2019]

2.3. AGROTECHNIC STEPS IN ASPARAGUS PRODUCTION

According Drost (2020) because plant performance varies widely between locations, cultivars, level of plant care and plant age, and in many cases the causes of variations cannot be identified, determining yield by assessing above-ground growth often leads to an overestimation of productivity. Achieving a good yield depends on the ferns remaining healthy throughout the vegetation and their ability to balance root regeneration and crown elongation throughout the summer. The most suitable place should be determined at least 2 years before starting asparagus cultivation, and it is a very important detail to choose an open place with full daylight. In addition, it is important to design the land for cultivation as long and rectangular. Since asparagus cultivation is a very long-lived plant, it can be infected with fungal diseases such as *Fusarium* spp. To prevent this, it should be removed from the crop rotation and different seed beds should not be made, and to prevent such a risk, grain can be produced to cultivate and strengthen the soil [Knaflewski 2005].

For asparagus cultivation, samples should be taken from different layers up to approximately 30 cm for soil analysis before planting. The soil samples taken should be sent to the chemical-agricultural station and examined to determine lime and mineral fertilization conditions. In order to adapt, the soil pH, which is very suitable for asparagus, must be at least 6 pH. It will also be very important to apply the advice and recommendations from the Chemistry and Agriculture Station to achieve the best yield [Reus 2006]. Since the sun angle changes as the temperature drops, planting orders should be adjusted accordingly in order for the plants to benefit from sufficient sunlight and achieve higher growth. Apart from this, asparagus plants can be grown in autumn due to the decrease in temperatures in spring and early harvest can be made from seedlings, but the use of seeds is also an alternative [Sergio et al 2019].

In asparagus cultivation, it is very important to use drained soil to develop a strong storage root structure. The root structure of the plant is seen to develop up to a depth of 10 ft in a well-drained soil. It does well in most soils as long as the water table does not come within 3 feets of the surface during the growth and development period. In mineral-rich organic soils, the growth of asparagus plants is very good and the yield is highIt is necessary to use plain fertilizer during soil preparation during the vegetation period and manure should be applied to increase and improve soil fertility. If necessary as a result of soil analysis, phosphorus, potassium and lime additives can be added before planting [Roby 2019].

Before starting asparagus cultivation, samples should be taken at depths of up to 30 cm in different layers during soil preparation and vegetation period. Although most asparagus varieties are adapted and thrive in less than optimal soil conditions, there is a high probability of reduced yields and shortening of the cultivation cycle. It is important to plant wind-blocking strips to protect young asparagus spears from the wind during the harvest period, especially in soils exposed to wind erosion at the beginning of vegetation, that is, in the spring. For crown cultivation, good quality seeds should be obtained and planted in soil where no asparagus has ever grown. The soil texture should be sandy so that the crowns can be dug easily and the soil does not stick. Phosphorus and potassium fertilizer should be applied according to the recommendations received as a result of the soil test and worked into the soil before planting in the crown bed [Brandenberger et al.2014].

When starting asparagus cultivation should be considered in detail and technically sufficient and it requires the development and understanding of a particular sales market. Asparagus cost is quite high. Therefore, it is necessary to have sufficient information. The initial investment is significant, with costs for establishing an asparagus plantation ranging from approximately 30,000 to 35,000 PLN per hectare. If successful, profit can be achieved within a few years. Asparagus fields last approximately 10 to 14 years [TopAgrar, 2024].

2.4. TOTAL ASPARAGUS PRODUCTION IN THE WORLD

According to the data published in the FAOSTAT system for 2022, asparagus production is in China, Peru and Mexico worldwide, with China accounting for approximately 87.1%, or 7.684 million tons, by a large margin. This large amount is due to China's large agricultural lands and favorable environmental conditions that enable farming. Peru and Mexico play a major role in the asparagus market and are countries that are highly focused on production to meet the global export demand, and these two countries, along with China, meet a large portion of global production. China ranks first in production with a total production area of 1.462.978 hectares, while Mexico ranks second with 37.218 hectares and Peru ranks third with 29.817 hectares. In Europe, Germany takes the lead with an area of approximately 20.370 hectares. Spain and Italy follow with 13.320 and 7.220 hectares of planting areas [Fig. 2 and 3].

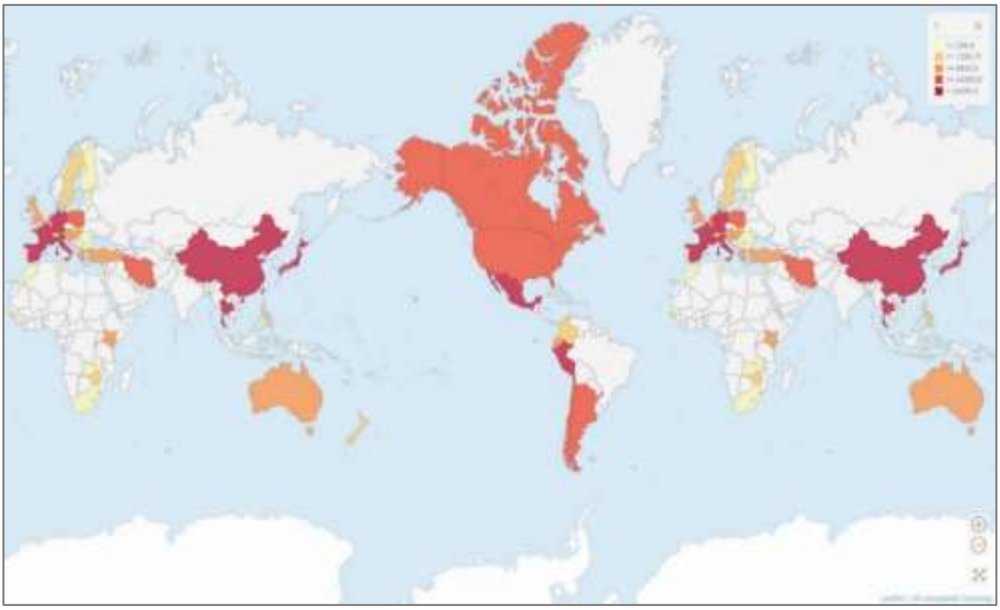

Fig. 2: Distribution of cultivation of Asparagus officinalis around the World [FAO 2023]

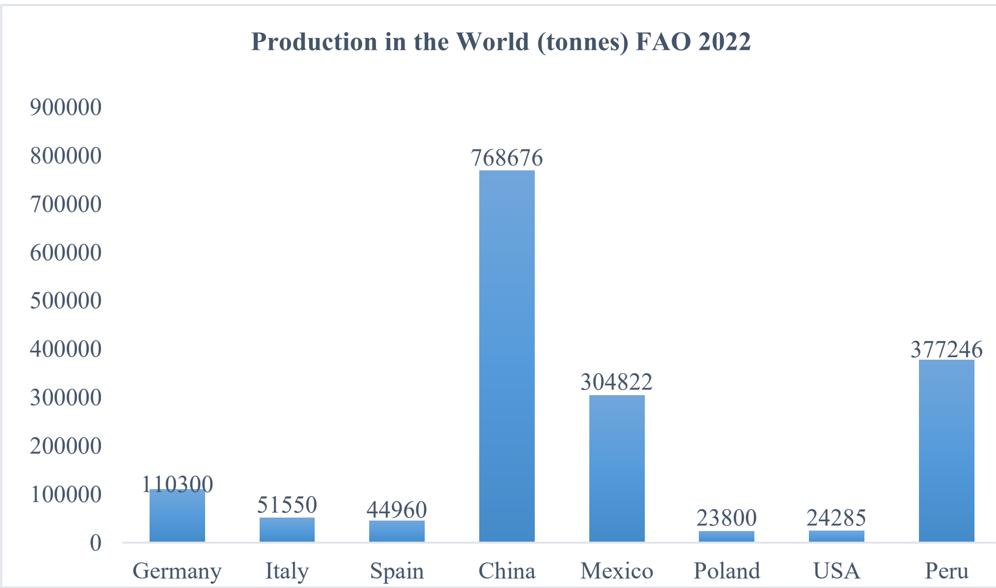

Fig. 3. Production asparagus in the World (1992-2022) [FAO 2023]

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According to FAOSTAT (2022) data, Poland has experienced a significant increase in asparagus production over the last decade. While the country's asparagus production was 2.75 thousand tons in 2013, it increased by 31.5% to 23.8 thousand tons in 2022. This growth reflects Poland's growing role in the global asparagus market and indicates an upward trend in agricultural production in this sector. The data highlights that Poland has made significant progress in asparagus cultivation and that production figures have steadily improved over the years. This upward trajectory strengthens Poland's position in global asparagus production and contributes to the growing international demand for the product [Fig. 4].

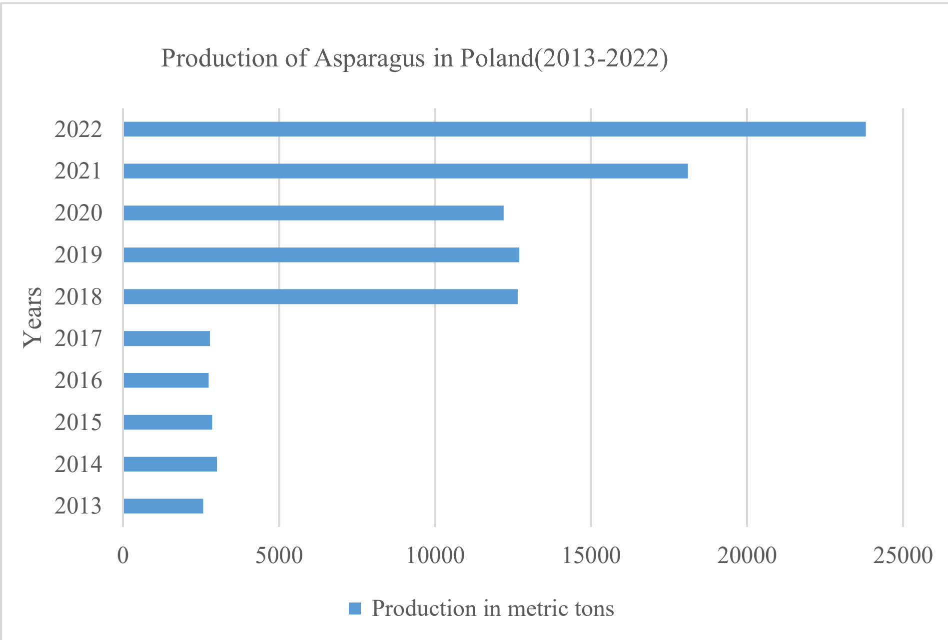


Fig. 4. Production of Asparagus in Poland (2013-2022) [FAO 2022]

2.5. CLIMATE AND SOIL REQUIREMENTS

Environmental factors have a significant impact on the cultivation of asparagus plants, so in most production areas with temperate and subtropical climates, temperature is the primary factor determining development and growth, as well as spear yield and asparagus quality [Chen et al. 2022]. It is a very important issue that in arid and semi-arid climate regions, water is a limited and expensive resource for agricultural activities. When irrigation water is extracted from excess underground water resources, it becomes environmentally critical. Despite this problem, intensive agriculture is carried out with perennial plants that consume a lot of water. An example of such a crop is green asparagus (*Asparagus officinalis* L.), and there are records of approximately 2.000 mm of applied irrigation per year for over-density fields [Rodríguez et al. 2022].

Excessive heat may cause a decrease in crop yield, especially in asparagus plants grown in microclimate regions, and may even cause the death of the plant (Hung et al. 2023].

While the asparagus plant adapts to most soil structures, it is much more suitable and productive in sandy, deep and loamy soils with good drainage, but it is still possible to produce efficiently in heavy soil structuresThe asparagus plant has a storage root structure that can go down to 10 meters deep in well-drained soils. Therefore, it is very important to use a well-drained soil. In addition, the asparagus plant can thrive in soils with high salt content, but has poor tolerance to excessive acidity. Most soils are acceptable if the water table does not come within 3 feet of the surface during the development period. Although the asparagus plant is highly tolerant of heavy soil conditions, acidic soils negatively affect plant life and yield. Asparagus plant prefers slightly acidic soils and a good yield is obtained for planting in soils with a pH range between 6.0 and 6.8 [Brandenberger et al. 2014].

Green asparagus is very sensitive to low temperatures and can be seriously damaged if the temperature drops below °C; also the growth rate is several days lower even after the temperature has increased [Falavigna 2008]. Green asparagus should not be grown in places with low soil temperature at -4 to -5 °C. Because it is very sensitive to cold harsh climatic conditions. The knots of the asparagus plant falling on the ground are resistant to low temperatures and it can be damaged by frost during the dry winter season. This affects sprouting and delays it. Generally, at 9 °C temperatures, spikes begin to grow [Biesiada et al 2007]. Asparagus does not like shady places, stony and wetlands. It requires open, sunny, fast-warming places with light, well-drained soils, especially free from weeds [Reus 2006].

Summer and autumn temperatures are important for the accumulation of grain nutrients and subsequent high yields, especially in the bud [Biesiada et al. 2007]. The knots of the asparagus plant falling on the ground are resistant to low temperatures and it can be damaged by frost during the dry winter season. This affects sprouting and delays it. Generally, at 9 °C temperatures, spikes begin to grow [Biesiada et al 2007]. Low temperature causes easier and stronger coloring of purple projections even after brief exposure to low intensity light. When water drought, excessive air temperature, extreme cold, and soil moisture are high, it prevents the growth of the pits. It causes plant spoilage as a result of early loosening of asparagus heads [Knaflewski 1981].

Preparation for plantation should starts two years before its establishment. The necessary soil profile tests should be carried out to determine whether the soil is suitable for cultivation, soil pH must be 6.0 - 7.0 [Sady 2006].
Heavy, loamy, crusty and stony soils are not suitable for asparagus plants. Because the ridges growing in such soils bend and the slow drying and warming of the soil in spring negatively affects the harvest period and causes it to be delayed [Spiżewski 2002]. For the asparagus plant, loamy rich sandy soil as well as loamy soil is the most effective soil and is the factor that increases the yield.

2.6. WATER REQUIREMENTS AND IRRIGATION

The most important factor in crop development and growth is water. In the world, irrigation in agriculture in general uses about 70% of the existing water resources, so a good improvement in irrigation methods will provide significant efficiency in water use [Cruz-Bautista et al. 2022]. Since herbaceous plants are very sensitive to water deficit, irrigation plays an important role in their development. Planning methods using indirect measurements of plant water demand (e.g. soil matrix potential) may not be advantageous (e.g. imprecise as it is not based on real plant demand, high risk of leakage in sandy soils), therefore planning the amount of water required by the plant using direct measurements (e.g. predawn leaf water potential (ψPD)) is more efficient and advantageous [Zinkernagel, Kahlen 2015]. In order to achieve the maximum production effects of a given cultivar, it is necessary to create optimal conditions for growth and development during the growing season - through appropriate fertilization and irrigation. Due to the specific cultivation method (spear harvest in early spring), the height and quality of the yield depends on the amount of ingredients stored in asparagus crown during the growing season of the previous year. Irrigation of asparagus in the current year after the harvest (postharvest irrigation/irrigation of summer stalks) causes the increase of the height, diameter of summer stalks and their number from one crown and positively affects the growth of the yield of spears in the following year [Rolbiecki et al. 2018].

There are several important water saving methods applied, including: deficit irrigation (DI), regulated deficit irrigation (RDI) and partial root zone drying [Consoli et al. 2017; Sepaskhah, Ahmadi, 2010]. DI is an approach that reduces the applied irrigation amount below the plant water requirement throughout the growth period [Capra et al. 2008; Oweis et al. 2011]. RDI provides sufficient water only during critical growth periods that may affect yield [Kirda, 2002; Katerji et al. 2008]. The most important method that minimizes the amount of water consumed in asparagus cultivation is the drip irrigation system. In this system, drip tape with spreader is used where water is applied slowly with low pressure. This drip tape can be placed as a subsurface system using "low flow" 15 mil drip tape placed at a depth of approximately 12 to 15 inches underground according to the plant row before planting seedlings or peduncles. One of the important advantages of this irrigation system can be counted as continuity of field operations (spraying, harvesting, etc.) during irrigation, gaining resistance to disease and increasing efficiency. Since the water distribution used in the drip irrigation system is spread evenly, it will provide water to areas twice as large as other irrigation methods (sprinkler, furrow). In addition, for the furrow irrigation method to be applicable, the field slope and soil type must be suitable, but it can be used in some specific cases. Mostly, the efficiency in terms of irrigation in furrow irrigation method is quite low and water usage is higher compared to sprinkler and drip irrigation systems [Brandenberger et al. 2014].

As a result of the intense water consumption pressure in agriculture, ways to make full use of available water and to increase water use efficiency have been sought. Recent increases in energy prices in particular have led many irrigators to consider how to use inputs to maximize the efficiency of their water resources [Stewar 2001].

According to Oliveira et al. [2012], when surface and sprinkler irrigation with contaminated water was applied, it was determined that E. coli O157:H7 remained alive in the soil and lettuce leaves, meaning that the irrigation regime caused bacterial transfer. Based on this, it was proven that the subsurface drip irrigation system reduces the risk of bacterial contamination compared to sprinkler and furrow irrigation [Fonseca et al. 2011]. The reason why drip irrigation system is preferred over wastewater irrigation systems is that it can prevent direct contact between wastewater and plants, thus reducing health and environmental risks [Campos et al. 2000]. Irrigation regime has an impact on crop production. It has been proven that drip irrigation systems can deliver water and chemicals to the root zone of plants more efficiently compared to other irrigation systems.

Advantages

- Water use efficiency is high, especially since surface runoff and deep infiltration or evaporation from the soil surface are greatly reduced or eliminated. Furthermore, the movement of chemical components or fertilizers through deep infiltration is reduced, thus preventing aquifer contamination.
- Use of poor quality water. Application of underground wastewater can prevent pathogen drift and reduce human and animal contact with such water.
- When applied properly in drip irrigation systems, fertilizer and pesticide application reaches the plant root zone directly and increases productivity. In crops with large distances, a smaller portion of the soil volume can be wetted, thus further reducing unnecessary irrigation water losses. Reductions in weed germination and weed growth generally occur in drier regions.
- Less labor required, less manual effort and injuries, and more utilization of dry land. Also, the possibility of intercropping is improved. Crop timing can be improved because the system does not need to be removed

during harvest or re-installed before intercropping. In addition, there is less damage to sidelines and sublines, and the potential for vandalism is reduced.
- Pressure is generally lower than in drip irrigation. This also reduces energy costs [Sinobas et al. 2012]

Disadvantages
- The biggest problem is the investment cost. This is the main problem with the SDI system and the initial investment cost is high compared to other irrigation systems.
- Management time, requirements for SDI can be higher than for other irrigation systems, especially the first couple of years when the learning curve is steep.
- Limited Dripline Lengths, in order to maintain high uniformity with SDI dripline lengths have to be limited. The maximum dripline length is a function of the dripline diameter, emitter flow rate, slope of the land and emitter spacing.
- Installation of an SDI system requires specialized equipment, is labor intensive, and represents a significant portion of the initial cost of the system [Efficiency 2005].

2.7. ORGANIC PRODUCTION

Organic agricultural production is undergoing a rapid transformation as the demand for healthier food and more environmentally sound production increases globally. Large producers are adopting organic practices to meet the growing demand [Smukler et al 2008]. Due to this organic growers must rely on biodiversity, cultural practices, alternative, environmentally friendly inputs. As a commercial crop, asparagus can be somewhat challenged to produce organically [Soytong et al 2018]. Organic fertilizers offer many benefits for horticulture. Firstly, they release nutrients slowly which means that plants are fed over a long period. Secondly, this slow release avoids over-feeding thus avoiding providing too much nitrogen, phosphorous or potassium, all of which can be harmful in too high doses. Thirdly, they create a good environment for beneficial soil organisms, such as earthworms, which improve the soil structure by incorporating organic matter well down into the topsoil creating drainage and air tunnels while so doing [Stein 2011].

Asparagus has excellent potential as a fresh crop for local markets. Organic crop production disallows the use of synthetic pesticides or conventional commercial fertilizers. Instead, organic growers rely on biodiversity, cultural practices, and alternative, environmentally friendly inputs [Kuepper 2002].

The main difference between organic and conventional food is in the method used in growing the food on the farm. In conventional food farming, farmers utilize chemicals during production and processing of farm produce. In organic farming, all the chemical which are utilized in conventional farming are avoided both in the food production and processing [Mounika et al 2019].

Organic production is the good principle of sustainable crop production, the form of farming which produces sufficient food to meet the needs of the present generation without eroding the ecological assets and productivity of life supporting systems of future generation [Shilpa 2014].

In organic production, crop cultivation is mostly dependent on nutrient transformations in the soil as the recycling of nutrients becomes more efficient. This is because the use of fertilizers is limited only to the amount allowed [Tu et al. 2006]. On the contrary, organic fertilizers are environmentally friendly additives e.g., microbial fertilizers, animal manure, compost and used in organic agriculture can be a good alternative and reduce the consequences of environmental pollution caused by synthetic fertilization [Onet et al. 2019; Umesha 2018]. Essentially, organic fertilizers, for example, gradually release primary and micronutrients into the soil, maintaining the nutrient balance for crop plants to grow and develop more healthily. They can also be an effective source of soil microbes while improving soil structure [Lewu et al. 2021].

2.8. NUTRIENT IN ASPARAGUS

For human health, consumption of vegetables and fruits creates significant effects especially in preventing diseases such as cancer, diabetes, cardiovascular and inflammatory diseases. The formation of phenolic compounds such as flavonoids, phenolic acids, tannins and phenolic diterpenes causes antioxidant effects. Providing biochemical and molecular mechanisms such dietary antioxidants reduce radicals caused by oxidative stress. For this reason, a continuous source of polyphenols is essential to provide preventive and defense mechanisms to reduce the risk of chronic diseases in humans [Scalbert et al. 2005]. The high polyphenol content in natural antioxidants has led to an increase in interest today [Barros et al. 2011; Gatto et al. 2011; Petropoulos et al. 2019]. In addition, it has led to a renewed interest in wild edible greens, which are considered an important and valuable natural antioxidant source due to their richness in minerals, organic acids, vitamins and essential fatty acids [García et al. 2014].

Asparagus is mostly consumed fresh, but less is used in processed form, such as pickled or fermented. This vegetable, which is widespread in many countries, is both cultivated and wild. It is highly valued for its biologically active components, nutritional value and sensory properties [Gębczyński 2007].

Asparagus, the plant with the highest content of antioxidant compounds among commonly consumed vegetables in the United States and Europe, is well known for its organoleptic properties and richness in nutrients and bioactive compounds. The main bioactive compounds in asparagus are phenolics, including phenolic acids and flavonoids, apart from important nutrients such as ascorbic acid and glutathione. Nutrients and phytochemicals in asparagus may act as health promoters that scavenge free radicals, prevent cell oxidation, and prevent heart disease and certain cancers [Sanae, Yasuo 2013].

Due to its delicious and special aroma, high eating quality and high nutritional value, green asparagus (*Asparagus officinalis* L.) has not been consumed much in recent years. However, the asparagus plant experiences rapid quality deterioration, including hardening, bad odor development, wrinkling and fresh weight loss, which is due to higher respiration [Mangaraj et al. 2009] and metabolic activities. The rapid loss of quality after harvesting of green asparagus poses a challenge in developing effective methods to delay quality decline and extend shelf life. It has been reported that the application of low-temperature modified atmosphere packaging (MAP) as an effective technology is beneficial for extending shelf life and preserving the quality of vegetables and fruits by reducing respiration rate and fresh weight loss, delaying ripening and minimizing physiological disorders and spoilage [Wang et al. 2018; Yoon et al. 2018].

2.9. FOOD NEEDS AND FERTILIZATION

Intensive soil fertilization with mineral fertilizers has led to several issues such as high cost, nitrate pollution and loss of soil carbon. Fertilization with organic matter such as compost therefore represents an alternative for sustainable agriculture. Traditional organic amendments such as manures, composts and sewage sludge have been extensively studied in the past. However, applications of biogas digestates and their impacts on the environment and human health are still unexplored. Recent articles report the agricultural potential and conflicting results of digestate performances. As a consequence, the effectiveness of digestate as organic amendment and fertilizer is still under debate [Nkoa 2014].

Crop production is currently expanding globally due to an increased demand for food, animal feed and biofuels; the latter has been stimulated by the increase in oil prices making bioenergy crops more competitive and profitable compared to fossil fuels [Winkler et al 2021]. Currently, 47.9 million km^2 are devoted to agriculture, which is about 50% of habitable land [FAO 2021].

Higher yields and better harvest quality can be achieved through the optimized use of fertilizers and the implementation of strategic production practices. Chemical fertilizers (also termed mineral, inorganic or synthetic fertilizers) contain a high concentration of a primary nutrient (nitrogen, N; potassium, K; phosphorous, P) as inorganic salts. Secondary elements (calcium, magnesium and sulfur) can also be added to soil by chemical fertilizers. Micronutrients (boron, manganese, iron, zinc, copper, molybdenum, cobalt and chlorine) [Dinca et al.2022] are in general absent in NPK chemical fertilizers and can be supplied by specific synthetic and expensive plant nutrients with soil or foliar applications [Thapa et al. 2021].

Inorganic and organic fertilizers have an important role in increasing agricultural production, but the use of mineral fertilizers is constantly growing, with an estimated total 186.67 million tons in 2016 [FAOSTAT 2021]. There is increasing concern regarding the negative environmental effects of chemical fertilizers. In fact, they can cause serious greenhouse gas (GHG) emissions and pollution of soil and water ecosystems. For example, synthetic nitrogen fertilizers have been recognized to be the most important factor contributing to direct N_2O emissions into the atmosphere as a consequence of their biodegradation by soil microorganisms [Chai et al 2019].

In addition, only 50–60% of synthetic nitrogen fertilizers added to soil is usually taken up by crops [Scherer 2005] and the rest runs off into water bodies (surface or groundwater) due to their high dissolution properties[Bijay 2021]. A possible alternative is the use of controlled-release fertilizers (coated and uncoated fertilizers with a low solubility) [Lawrencia 2021] but they are expensive and, therefore, used mainly for high-value crops (e.g., vegetables, fruits, flowers, ornamentals) [Scherer 2005]. Inhibitors of nitrification and urease processes can also be used for maintaining N in its soil-stable form by slowing its conversion to nitrate or delaying the first step of degradation of urea [Wang et al.2021].

Fertilization allows to create programs based on optimal concentrations and proportions for plants between individual ions in a solution close to the root system of plants. This method of fertilization results in a more effective use of ions, while giving the opportunity to synchronize the application of fertilizers with the needs of plants. No fertilizer was given for storage. The amount and concentration of fertilizers depends on the age, plant development phase and weather conditions [Karczmarczyk 2006].

Rules to be followed in fertilizing asparagus according to Schulze [2007]:

1. Fertilization should be applied in appropriate quantities and dates so that the fertilizers can be used by plants during growth.
2. Make fertilization dependent on: the demand related to yielding and quality, the amount of soil components, the amount of calcium and organic matter, growing conditions, other ingredients contained in the plants.
3. Depending on your needs, apply single doses of potassium and nitrogen several times.
4. Quickly mix fertilizers with soil (losses of ammonia).
5. Fertilization should be applied using a modern technique that does not bring losses (proper dosage, even fertilization).

3. SOIL AND METEOROLOGICAL CONDITIONS
3.1. SOIL CONDITIONS

The field experiment was carried out at light soil (V), i.e. the arable land medium quality. Based on the percentage of granulometric fractions for experimental field, the tested soil should be classified as a sand granulometric group and a loamy sand subgroup [PTG 2009]. The soil contained on average 78.8% of the sand fraction, 19.7% of the silt fraction, and 1.5% of the clay fraction. Analyzing the percentage of the <0.02 mm fraction, the tested soil in the 0-60 cm layer was classified as a light soil.

Considering the granulometric composition down to a depth of 0.6 m, the soil can be classified as category II in terms of drought susceptibility. Soils in this category are characterized by limited water capacity, i.e., the water generally available to plants is in the range of 127.5-169.9 mm [Doroszewski et al. 2012].

The low water capacity of the experimental field results in poor water supply to the plants. The groundwater table in the field area was below 1.5 m deep during the growing season, which had no impact on water management. The study area was characterized by precipitation-dependent soil water management. Due to its limited water capacity, the soil had a poor ability to continuously supply water to the plants. Effective water retention in the 0-60 cm controlled moisture layer was 50.9 mm (tab. 1).

Table 1. Selected water properties of the soil at the experimental field [mm]

Depth (cm)	Water supply (mm)			effective retension (mm)	effective useful retension (mm)
	field water capacity	critical moisture	permanet wilting point		
0-30	60.0	30.1	11.2	48.7	29.9
30-60	42.0	21.0	5.1	36.9	21.0
0-60	102.0	51.1	16.3	85.6	50.9

The soil of the experimental field, in both the surface and subsurface layers, was characterized by low levels of phosphorus and potassium (tab. 2). The content of available magnesium in both layers indicated an average content of plant-available magnesium. The iron content in the surface layer indicated an average content, while in the subsurface layer it was low. The soil pH in the 0-30 cm layer was neutral, and in the 30-60 cm layer it was slightly acidic. Measurement of the pH in a 1M KCl solution indicated an unnecessary need for liming. The soil was relatively rich in organic carbon, with an average content of 23.1 g kg^{-1}.

Table 2. Selected soil parameters

Parameter	Layer 0-30 cm	Leyer 30-60 cm
pH in 1M KCl	6.6 ± 0.28	6.5 ± 0.26
C organic (g·kg^{-1} s.m.)	23.10 ± 0.50	6.3 ± 0.37
P_2O_5* (mg·kg^{-1} s.m.)	37.0 ± 2.57	31.0 ± 1.97
K_2O* (mg·kg g^{-1} s.m.)	52.1 ± 3.95	33.7 ± 2.14
Mg* (mg·kg g^{-1} s.m.)	33.20 ± 4.51	28.0 ± 3.00

* – content available to plants

3.2. METEOROLOGICAL CONDITIONS

The precipitation and thermal conditions during the field study were characterized by significant variability. The highest average temperature in the growing season occurred in 2019 - 15.9°C (+1.1°C compared to the average for the multi-year period 1991-2020). The lowest average temperature in the growing season, which was equal to the average temperature for the multi-year period 1991-2020 (14.8°C), was recorded in 2020 and 2021. In the 4-year study period, in the first 2 months of the growing season (except for April 2019), lower temperatures were recorded in relation to the multi-year average, which, combined with variable precipitation during this period (tab. 3). The average monthly temperatures in the studied growing season were higher than the multi-year values for the months of June-September, while lower in April and May. The highest temperature differences in relation to the multi-year period were found in June (+3.2°C) and July (+3.3°C). The 2019-2023 study period was characterized by lower precipitation in relation to the multi-year average values, except for 2020. The average rainfall in 2019-2022 for the growing season was 307.8 mm and was 16.6 mm lower than the multi-year average. The lowest precipitation was recorded in 2021, amounting to 260.7 mm during the growing season. This constituted 80.3% of the multi-year precipitation. The highest precipitation was observed in 2020, amounting to 435.5 mm, which constituted 134.2% of the multi-year precipitation. The highest monthly precipitation was recorded in May 2020, amounting to 153.9 mm, which constituted 35.3% of the seasonal water dose in 2020 (tab. 4). The longest drought periods in the entire 4-year vegetation period were recorded for the months: June-August in 2019, June-September in 2021, April-July in 2022.

Table 3. Air temperatures in the 2019-2023 growing seasons with reference to the multi-year average in the Bydgoszcz region* (^{o}C)

Period	Decade	Month						Mean
Year		IV	V	VI	VII	VIII	IX	IV–IX
1991-2020	**I–III**	**8.3**	**13.2**	**16.7**	**18.9**	**18.2**	**13.3**	**14.8**
2019	I	7.6	8.8	21.4	16.0	18.7	15.8	
	II	6.5	12.3	22.8	18.0	19.0	12.0	
	III	13.7	15.0	21.6	21.6	21.2	12.7	
	I–III	**9.3**	**12.1**	**21.9**	**18.6**	**19.7**	**13.5**	**15.9**
2020	I	7.3	11.2	14.9	17.9	20.1	14.3	
	II	7.0	19.6	19.5	17.8	20.0	14.7	
	III	10.4	12.0	19.4	18.3	17.7	17.4	
	I–III	**8.2**	**10.9**	**17.9**	**18.0**	**19.2**	**14.4**	**14.8**
2021	I	3.7	8.8	17.8	19.8	17.9	14.3	
	II	7.3	15.1	20.4	21.2	18.3	14.4	
	III	6.0	11.8	21.2	20.7	15.0	12.2	
	I–III	**5.7**	**11.9**	**19.8**	**20.6**	**17.0**	**13.6**	**14.8**
2022	I	4.3	12.1	16.4	18.5	20.6	13.7	
	II	7.1	14.7	17.9	18.5	23.2	12.1	
	III	9.4	12.9	21.6	20.3	20.0	9.6	
	I–III	**6.9**	**13.2**	**18.6**	**19.2**	**21.2**	**11.8**	**15.2**
2023	I	4.4	10.1	17.9	19.6	17.0	17.8	
	II	9.1	13.5	18.3	20.8	22.4	17.7	
	III	9.9	16.0	19.9	18.3	18.4	16.7	
	I–III							
2019-2023	**Mean**	**7.5**	**12.0**	**19.6**	**19.1**	**19.3**	**13.3**	**15.1**
Difference to multi-year average		-0.8	-1.2	+2.9	+0.2	+1.1	0	+0.3

*- measuring station located in Mochełek.

Table 4. Precipitation in the 2019-2023 growing seasons with reference to the multi-year average in the Bydgoszcz region* (°C)

Period / Year	Decade	Month IV	V	VI	VII	VIII	IX	Mean IV–IX
1991-2020	**I–III**	**25.8**	**55.1**	**56.6**	**77.4**	**60.3**	**49.2**	**324.4**
2019	I	0	9.3	0	14.7	27.3	57.2	
	II	0	56.4	16.2	2.0	4.2	9.9	
	III	1.5	23.5	1.5	5.7	6.2	31.4	
	I–III	**1.5**	**89.2**	**17.7**	**22.4**	**37.7**	**98.5**	**267.0**
2020	I	0	16.4	63.0	32.5	32.7	32	
	II	0	11.0	33.5	47.1	3.2	0	
	III	0.7	7.2	57.4	5.5	54.1	39.2	
	I–III	**0.7**	**34.6**	**153.9**	**85.1**	**90.0**	**71.2**	**435.5**
2021	I	7.6	30.2	5.2	23.3	13.9	0	
	II	16.9	21.7	8.8	17.4	8.2	30.5	
	III	5.9	17.6	19.8	0	28.5	5.2	
	I–III	**30.4**	**69.5**	**33.8**	**40.7**	**50.6**	**35.7**	**260.7**
2022	I	11.5	3.6	11.4	34.1	6.0	26.0	
	II	10.9	7.5	22.7	5.4	49.0	11.4	
	III	0	16.5	8.1	7.8	14.0	21.8	
	I–III	**22.4**	**27.6**	**42.2**	**47.3**	**69.0**	**59.2**	**267.7**
2023	I	8.7	11.7	0.0	10.4	27.7	0.0	
	II	8.4	12.2	10.6	17.2	7.6	4.4	
	III	9.6	1.5	21.2	47.6	31.8	2.9	
	I–III							
2019-2023	**Mean**	**13.8**	**55.2**	**61.9**	**48.9**	**61.8**	**66.2**	**307.7**
Difference to multi-year average		-12.0	+0.1	+5.3	-28.5	-1.5	+17.0	-16.7

*- measuring station located in Mochełek.

4. MATERIAL AND METHODS

4.1. EXPERIMENTAL SITE AND LOCATION

The experiment was carried out in the years 2019-2023 in Ecological Farm in Luchowo close to Łobżenica, 60 km west of Bydgoszcz (latitude 15s'; longitude 17s 15'; height 91 m above sea level. The research was carried out on an individual (private) farm (fig. 5).

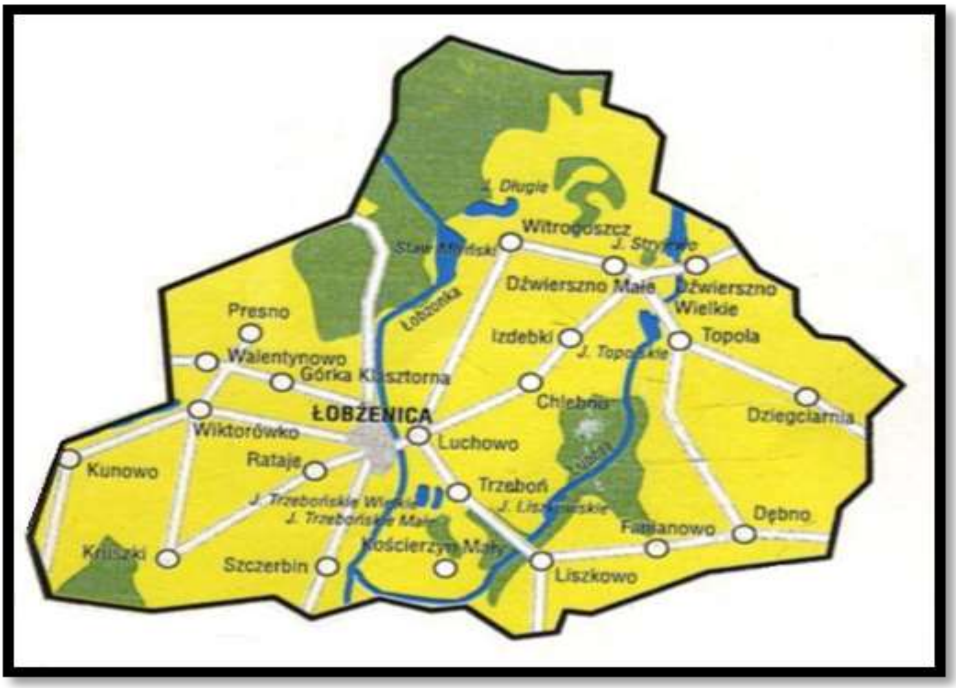


Figure 5. Map about location of field experiment

4.2. EXAMINED FACTORS AND FIELD DESIGN

Two factors were examined in the experiment and were as follows:

I factor – subsurface drip irrigation

- O – without irrigation (control),
- D – with subsurface drip irrigation,
-

II factor – cultivars:

- A – ‘Cumulus’,
- B – ‘Bacchus’
- C – Gijnliym
- D – Mondeo

Dutch cultivars as 'Cumulus', 'Bacchus', 'Gijnlim' and the German cultivar Mondeo were determined (fig. 6). The asparagus cultivars used in the study were preferred because they are more compatible with Polish climate conditions. Seeds of the asparagus used for the study were ordered from Rosen Deutsche Spargelzucht Company more details. The plan of the experiment was suitable for experimental methodology and statistical analysis. The 3 replications established in each variant. At each replication, 20 seedlings (plants) planted with the distance of 0.35 m and 0.7 m between the replications. 2.20 m distance left between the factors (rows).Totals of 60 plants of each cultivar were planted in single variant. For all experiment 120 pcs for one cultivar were planted (O and D).

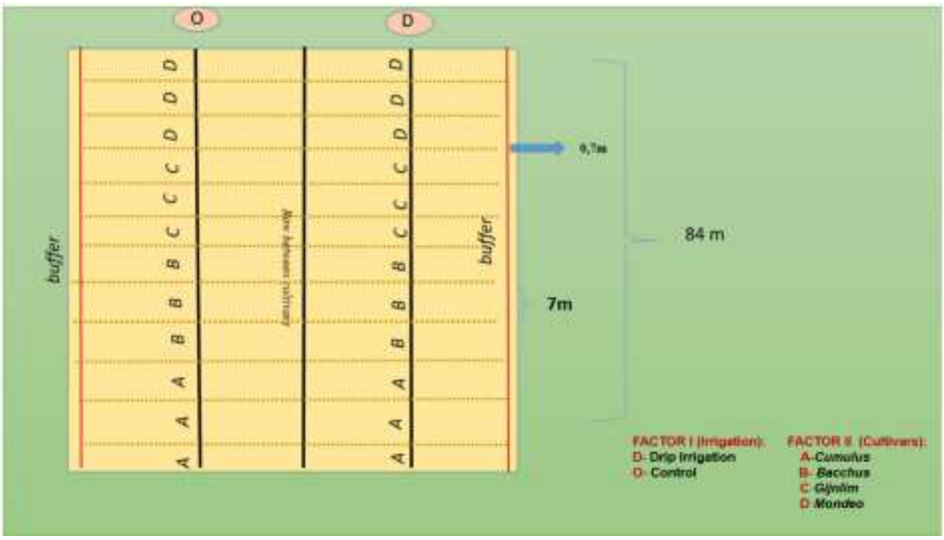


Fig. 6. Scheme of experiment

In the experiment, a single dose of manure at a rate of 40 t ha^{-1} was applied prior to the experiment’s establishment in 2019. No fertilization was applied in the subsequent years of the experiment.

4.3. IRRIGATION METHOD

For subsurface drip irrigation, an ‘Euro Drip’ drip line was used, which usually delivers approximately 5 L of water per metre, which is sufficient for asparagus depending on soil and climatic conditions. Water used for irrigation was taken from a well located in the experimental field. Watermark tensiometer were used to determine the date of irrigation and allowed the soil water potential according to Horticultural Institute in Geisenheim Germany [Paschold, Wiethaler

2000]. The irrigation was started when the soil moisture was close to -40 kPa. This value was pf 2.7, which corresponded to the depletion of 50-60% of available water content. Irrigation season was started from April to August in 2019 and from June to August in 2020-2022. The single irrigation water doses have been based on rainfall conditions and actual soil moisture measured by the temsiometer and amounted from 4 to 15 mm (tab. 5).

Table 5. Pentade and seasonal doses of water used for irrigation on the drip plots in mm

Water variant	Year	Months																		Seasonal irrigation dose
		June						July						August						
		Pentads																		
D	2019	6	6			6	6		4	6	6	6	6			12	12			76
	2020						6	6				6	12			16	16			62
	2021					6	6		12	12	6	12	15	6	6	12	15		6	114
	2022					12	12				12	12	12	15	12		6	12	6	111
	Mean																			**91**

D – drip irrigation

4.4. CULTIVARS CHARACTERISTIC

- Dutch cultivar: ‘Cumulus, ‘Bacchus’ ‘Gijnliym’

The ‘Cumulus’ cultivar of asparagus, which is regionally found in the northern and central parts of Europe, is a 100% male hybrid and is an early cultivar with a very high yield. It is very tasty in taste and is suitable for under cover, tunnel or mini tunnel cultivation. The recommended planting density for this variety is four plants per linear metre. This cultivar is of very high quality, with smooth, shiny and thick stems, but a slightly pale variety with a white colour. The leaves are very branched and large, with closed tips. It is resistant to rust and it is essential to keep the ratio between calcium, magnesium and potassium in an optimum way to increase the durability of the leaves [Beeren Plantproducts 2025].

‘Bacchus’, which is especially cultivated in the north of Europe, is a 100% hybrid variety that does not contain anthocyanin. This cultivar, which has a very high yield, is early and is grown in tunnels or small tunnels. It is of very good quality and produces a single type with closed ends. The recommended planting density is 5 and 6 plants per meter. ‘Bacchus’ cultivar is highly resistant to diseases, upright, tall and robust [Thwan van Gennip 2025].

The ‘Gijnlim’ cultivar, which is more compatible with temperate regions in terms of climate, is a 100% male hybrid and can be grown in both white and green forms and has a very high production potential. One of the reasons for this is that it is a very early cultivar. In terms of soil conditions, it is very compatible with both sandy and clayey soils, and the stronger the soil, the thicker the stem will remain the same until the end of the season. The tips have very good closure, are flat, smooth and very strong against rust. Its consumption is very common. The recommended planting density is approximately 4 plants per meter [Thwan van Gennip 2025].

• German Variety: 'Mondeo'

The 'Mondeo' cultivar is suitable for planting in spring and is ready to harvest between April and July and has very tasty and high quality stems. It is also a 100% male hybrid. It likes a bright environment for growth and is a versatile cultivar. It has very high resistance to diseases. Higher yields are obtained in well-drained beds for planting [Dobies 2025].

4.5. MEASUREMENTS AT THE FIELD

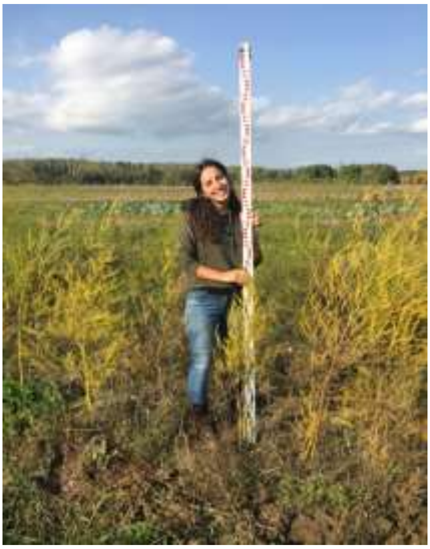
4.5.1. Harvesting of green spears

During harvesting period number of spears per plant (pcs/plant) and weight (kg) were estimated. The asparagus spears were harvesting every second-third day of the harvest period (pic. 1). Spears were cut when the height was 20 cm. During the each single harvest, the spears were counting and weighting for each replication of experimental factors (total 24 single plots). The total harvested yield was separated for marketable and non-marketable yield. The green spears samples at the field was collected for analysis on each harvesting period as planned. During harvesting period green spears were weighted by digital scale (Cas pr II brand) and counted. Samples were collected twice during the harvest period for laboratory process at the third decade of May- third decade of June in 2020-2023. Each single sample from replication was around 150 g. For one cultivar and two variants was 900 g. For all experiment 4500 g for each samples collections.

Picture. 1. Picture from the harvest of asparagus green spears

4.5.2. Measurement of summer stalks

Measurements were done with the tape measure (height), caliper (digital diameter), and digital scale (weight of summer stalks) equipment. The summer stalks were measured at beginning of October for each year from 2019 to 2022 (end of vegetation season) (pic. 2).




Picture. 2. Pictures from measurement of summer stalks by Hicran Sadan-Ozdemir

4.6. CHEMICAL ANALYSES OF ASPARAGUS GREEN SPEARS

4.6.1. Chlorophyll and total carotenoids determination

The samples of asparagus green spears collected in the organic farm in Luchowo close to Łobżenica (60 km west of Bydgoszcz) were analyzed in Bydgoszcz and Kaposvar. The samples were collected in the four vegetation period during the harvest time in years 2020, 2021, 2022 and 2023.

Estimation of total chlorophyll (a+b), carotenoids, anthocyanin, dry mass and the % content of total ash were analyzed at Department of Biotechnology of Bydgoszcz University of Science and Technology, Faculty of Agriculture and Biotechnology (pic. 3).

Measurements of physiological parameters included the concentration of assimilation pigments (chlorophylls, carotenoids). In order to determine them,

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chlorophyll and carotenoids in asparagus spears material were extracted with chilled 80% acetone. The middle parts of asparagus shoots were selected for measurements. The chlorophyll content was determined according to the method of Arnon et al. [1956], with a modification of Lichtenthaler and Wellburn [1983], and the concentration of carotenoids according to the method of Hager and Mayer-Berthenrath [1966]. Extracts from middle part of asparagus green spears were obtained by grinding samples of green mass weighing 100 mg in a mortar with 10 cm^3 of 80% acetone. The homogenates were then centrifuged for 10 minutes at 1500 rpm. The content of chlorophyll a, chlorophyll b and carotenoids was determined spectrophotometrically (Eppendorf BioSpectometer) by measuring absorbance at wavelengths of 663 nm, 645 nm and 440 nm, respectively. By using formula the readings were calculated. Total chlorophyll concentrations were calculated using the following equation:

$$\text{Total chlorophyll} = 20.2(A645) + 8.02(A663)\ [mg \cdot dm^{-3}],$$

where

A645 – absorbance at $\lambda = 645$ nm
A663 – absorbance at $\lambda = 663$ nm

The concentration of the total carotenoids was calculated according to the formula:

$$\text{Total carotenoids} = 4.695 \cdot A440\ [mg \cdot dm^{-3}],$$

where

A440 – absorbance at $\lambda = 440$ nm

The results of the total chlorophyll and carotenoids obtained for pigment content were expressed in $mg \cdot kg^{-1}$ fresh plant weight (f.w.).

Picture 3: Analysis were made for physiological parameters of asparagus green spears (by Hicran Sadan-Ozdemir)

4.6.2. Total anthocyanins determination

Anthocyanins were extracted from middle part of asparagus green spears of 200 mg, with 1% HCl in methanol. The absorbance was measured at the wavelength corresponding to the maximum of the anthocyanin band (for cyanidin-3-glucoside–530 nm). The concentration of the total anthocyanins was calculated following the formula [Harborne 1967].

Total anthocyanins = A530 / h·k [$g \cdot dm^{-3}$],

where
A530 – absorbance at λ = 530 nm
h – layer thickness – 1 cm
k – specific extinction coefficient for cyanidin-3-glucoside = 61.7

The results of the total anthocyanins obtained for pigment content were expressed in $mg \cdot kg^{-1}$ fresh plant weight (f.w.).

4.6.3. Estimation of dry mass and the % content of total ash

Estimation of dry mass and the % content of total ash were analyzed at Department of Biotechnology of Bydgoszcz University of Science and Technology Faculty of Agriculture and Biotechnology. Dry mass was determined based on the weight of plant material dried in a dryer for 48 h at 105°C and given in %. he total dry matter content of the asparagus spears were determined of using the drying technique according to the methodology of the Association of Official Analytical Chemists [AOAC 2002].

The % content of total ash, i.e. minerals (calculated on dry weight), was determined in asparagus spears. This method involved incinerating an analytical sample of the dry mass of leaves in a muffle furnace at a temperature of 550ºC ± 25ºC until the organic substances were completely burned and determining the residue by weight (pic. 4).

Picture 4: Dry mass of asparagus green spears (by Hicran Sadan-Ozdemir)

4.6.4. Estimation of the level of K, Mg and Ca

Estimation of K, Mg and Ca were analyzed at Institute of Plant Production Department of Agronomy in MATE, Hungary. The level of elements was analyzed by Atomic Absorption Spectrometry [Welz, Sperlin 1999].
In the dry mass, of asparagus green spears the total content of Mg, K, and Ca was determined using the atomic absorption spectrophotometry (ASA) method – using the PHILIPS PU 9100X spectrometer.

4.7. SUMMER STALKS HEALTHINESS

Occurrence of asparagus rust, grey mould (*Botrytis cinerea*), *Stemphylium* leaf spot and stem rot (*Fusarium* spp.), were evaluated. Infection degrees of fern for first three diseases, and percentage of stems with symptoms of Fusarium rot were estimated. Fifty stems from each plot were chosen for the evaluation. Plant infection level was evaluated at the end of the vegetation periods in the years 2019-2022, according to a 9-degree scale where 0 meant healthy plants, and a score of 1 to 8 indicated percentages of the plant's surface with disease symptoms of respectively: 0-5%; 6-15%; 16-25%; 26-35%; 36-45%; 46-60%; 61-80%; 80%) and more.

Infection degrees were transformed into infection indexes according to Townsend and Heuberger formula [Wenzel 1948]. Obtained data were statistically analyzed using analysis of variance. Mean values were tested with Tukey's test.

4.8. WATER NEEDS OF ASPARAGUS

4.8.1. Field water consumption (S)

Field water consumption (S) is one of the basic measures of water needs, assuming that water reserves in the soil are maintained within the range of easily accessible water (EAW) for plants. In such a case, field water consumption can be classified as ET_c measured for a specific species. This condition must last throughout the period for which field water consumption is calculated. In the field experiment with asparagus plants, optimal moisture conditions were obtained on objects irrigated with a subsurface drip system. Field water consumption was calculated for irrigation period (VI-VIII) when summer stalks of asparagus were irrigated.

Field water consumption was calculated using the equation [Drozd and Nowak 2006]:

$$\mathbf{S = Wp + P - Wk} \qquad \mathbf{(1)}$$

where:

S – field water consumption (mm),

Wp – initial humidity (mm),

Wk – final humidity (mm),

P – water revenue (effective precipitation + irrigation) (mm).

Initial moisture (Wp) and final moisture (Wk) were determined based on soil suction pressure readings from Watermark soil sensors (reading in kPa), for two soil thickness levels: 0-30 cm and 30-60 cm, i.e. a controlled-moisture layer. The 0-60 cm layer usually contains over 80% of the plant root system [Drost 1996].

Moisture content in % by volume [$cm^{-3} \cdot cm^{-3}$] was determined from soil retention curves in the range of available water content. The soil retention curve for the

controlled-moisture layer was plotted based on the soil granulometric composition using the indirect Varallyay method [Varallyay and Mironienko 1979].
Based on the pF curves for the experimental soil, soil moisture was determined in % by volume and water content was calculated for the controlled-moisture layer [Drozd, Nowak 2006]:

$$Q = W_a \cdot h/10 \qquad (2)$$

where:
Q – water reserve (mm),
Wa – moisture content in % by volume,
h – soil layer thickness (cm),
10 – water conversion factor from $t \cdot ha^{-1}$ to mm H_2O.

The result of the above formula was used to calculate the field water consumption for the growing season from a controlled-moisture layer (up to 60 cm depth). This allowed determining the water demand during the growing season of asparagus. Water consumption was balanced in pentad periods, then the decade, monthly and seasonal consumption was calculated for the water variants tested in the experiment. The average daily water consumption in the months of the growing season was also calculated.

4.8.2 Reference evapotranspiration (ET_o)

The Hargreaves model in the Droogers and Allen modification is an alternative to the Penman-Monteith model for determining ET_o, which generally requires more input data (Allen et al. 1998). The calculation is performed according to the formula:

$$ET_o = HC \cdot Ra\,(T_{max} - T_{min})^{HE} \cdot [(T_{max} + T_{min})0.5 + HT] \qquad (3)$$

where:
ET_0 – reference evapotranspiration (mm),
HC – authors’ empirical coefficient = 0.0025,
Ra – radiation above the atmosphere [mm/day^{-1}],
Tmax – maximum air temperature (°C),
Tmin – minimum air temperature (°C),
HE – authors’ empirical coefficient = 0.5,
HT – authors’ empirical coefficient = 16.8.

The reference evapotranspiration was calculated using the Hargreaves model for a single day. Then, the obtained ET_o values were balanced for decadal, monthly and annual periods. The meteorological data were obtained from the meteorological station of the Department of Biogeochemistry, Soil Science, Irrigation and Drainage of the Bydgoszcz University of Science and Technology in Mochełek near Bydgoszcz.

4.8.3. Crop evapotranspiration (ET_c)

Data obtained from S and ET_o values were used to calculate the plant coefficient k_c in order to determine the potential evapotranspiration of asparagus in the applied irrigation period. The values of the coefficients k_c were calculated using the formula:

$$\mathbf{k_c = S/ET_o} \qquad (4)$$

where:
k_c – plant coefficient for calculating ET_c,
S – field water consumption
ET_o – reference evapotranspiration (mm).

The values of plant coefficients (k_c) were calculated for the Hargreaves model in the Droogers and Allen modification. The k_c coefficients were determined for the tested for asparagus for each month of the irrigation season (June-August) from the second year of cultivation. To calculate the crop evapotranspiration on a surface with limited wetting (ET_{cD}), the following formula was used [Vermeiren, Jobling 1984]:

$$\mathbf{ET_{cD} = ET_o \cdot k_c \cdot k_r,} \qquad (5)$$

where:
ET_{cD} – crop evapotranspiration for drip-irrigated area(mm),
kr – reduction (correction) factor,
kc – plant factor,
ET_o – reference evapotranspiration (mm)

Based on the percentage value of ground surface shading by plants, the k_r coefficient values were adopted according to Treder [Treder 2021] (tab. 6).

Table. 6. Values of the correction factor kr according to Treder

Ground surface shading (%)	Coefficient value k_r
10	0.28
20	0.48
30	0.65
40	0.80
50	0.90
60	1.0

4.9. SOIL ANALYSES

The particle size distribution of the prepared samples was determined using laser diffraction with a MALVERN MS 2000 analyzer. pH values were determined potentiometrically using a pH meter (in 1M KCl salt solution). Organic carbon content was determined using a Vario Max CN analyzer. K, Mg, and Ca content was determined using an ASA Thermo Solaar S4 instrument. The properties of the soil samples were tested at the Institute of Plant Production, Department of Agronomy, MATE, Hungary.

4.10. STATISTICAL ANALYSIS

The measurements of the basic parameters of the asparagus summer stalks (cm), i.e. height (cm), number of the asparagus summer stalks (pcs), number of summer stalks from one plant and it diameter (mm) at a height of 3-5 cm from the ground surface were made. Parameters of the asparagus green spears: marketable yield ($t \cdot ha^{-1}$), weight (g), number (pcs), bioactive components of the asparagus green spears: total chlorophyll (mg kg^{-1} FW), total carotenoids (mg kg^{-1} FW), antioxidant activity (mmol $Fe^{2+}kg^{-1}$).were tested for differences by two-way ANOVA using of Statistica® 13.1 package. The significance of differences (HSD—honestly significant difference) was evaluated using the Tukey multiple confidence intervals for the significance level of $p = 0.05$. Correlation coefficients were determined using an EXCEL spreadsheet.

5. RESULTS AND DISCUSSION

5.1 CHARACTERISTIC OF SOIL MOISTURE CONDITIONS

The water potential of the experimental soil during the experiment period showed variability and depended strictly on the rainfall distribution and subsurface irrigation doses (fig. 7-10).

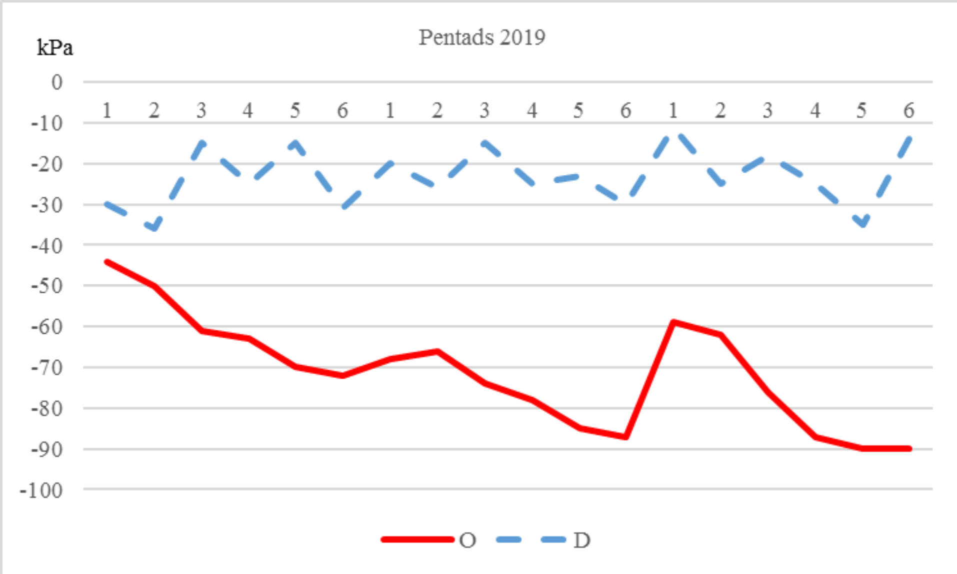
Analyzing the moisture conditions of the experiment for the 0-30 cm and 30-60 cm layers confirmed the validity and correctness of irrigation. Drip irrigation treatment (D) did not exceed the water potential limits to -50 kPa. Slight differences in soil water potential were observed between the thickness layers in each year of the study.

For the control condition (O), soil water potential was closely dependent on rainfall conditions and was highly variable. In the control plots, water potential decreased throughout the growing season to -90 kPa, significantly exceeding critical values, with the exception of 2020, where the decrease occurred only at the beginning of the growing season and remained at a level readily accessible to plants throughout the rest of the season. Comparing water potential between the 0-30 cm and 30-60 cm soil layers reveals that greater moisture fluctuations occurred in the 0-30 cm surface layer. The highest water deficit was observed in 2021, and the lowest in 2020.

The measured soil water potential values in the drip irrigated plots (D) indicate that irrigation control using the tensiometric method was and is a method that ensures proper monitoring of soil moisture, which determines irrigation effectiveness. Similar conclusions were reached by Pogue and Dooley [1985], Pacholak [1986], Sterrett et al. [1990], and Paschold and Wiethaler [2000]. In their recommendations for irrigation of field-grown vegetables, Kunzelmann and Paschold [1998a, b] and Paschold and Kunzelmann [2002] recommend the use of the tensiometric method for micro-irrigation control, primarily drip irrigation.

Close trends of course and values of the soil water potential under conditions of vegetative irrigation in perennial crops were observed, among others, by Pacholak [1986] in an orchard, Żakowicz [2010] in reclamation plantings, Rolbiecki [2013] in asparagus cultivation and Sositko [2019] in phytomeliorative plantings of lime and birch.

The soil moisture conditions for drip irrigation confirmed the usefulness of installing a subsurface drip irrigation system in organic farming asparagus maintaining favorable moisture conditions on light and very light soils. The usefulness of this irrigation system is also confirmed by experiments with asparagus as well as with other plant species grown in very light soil conditions, among others, by Rolbiecki [2004, 2007, 2013, 2021], Rolbiecki et al. [2018], Żarski et al. [2004].



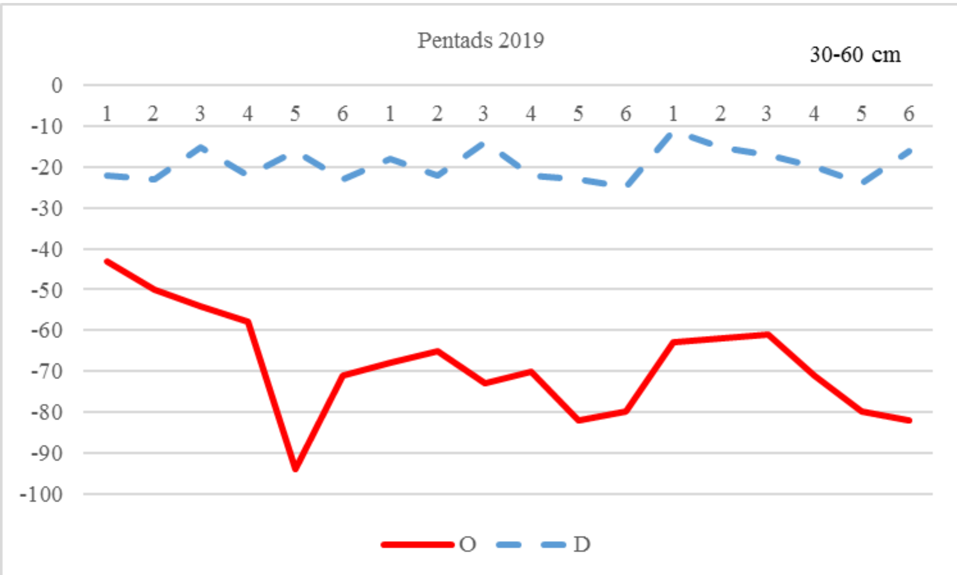
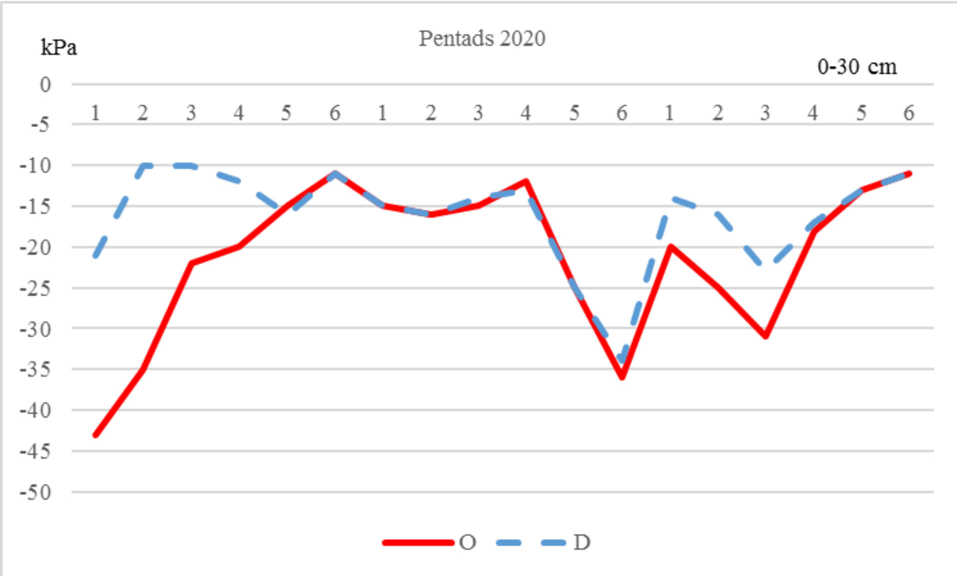


Fig. 7. Soil water potential in kPa for different water variants: O and D, two levels of soil depth: 0-30 cm and 30-60 cm in the year 2019



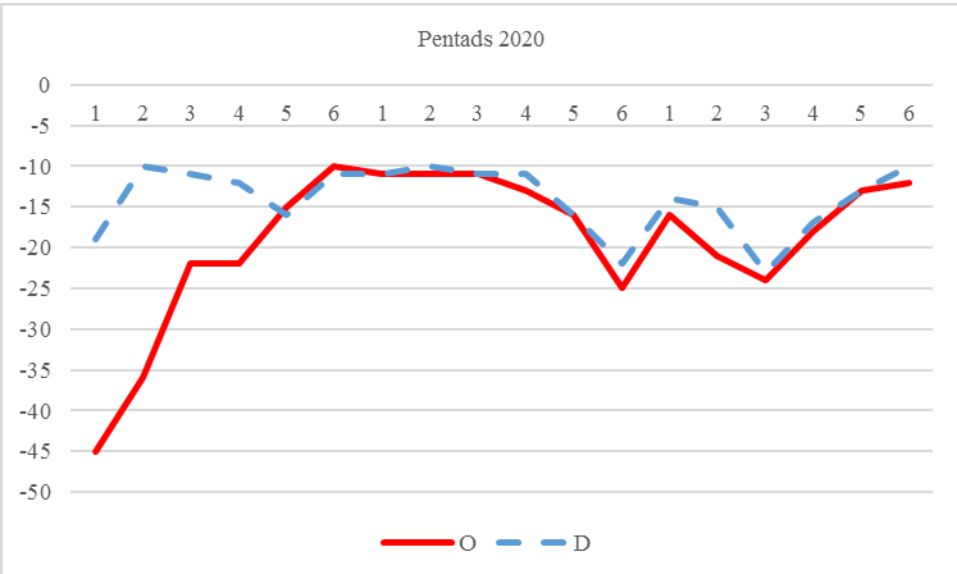
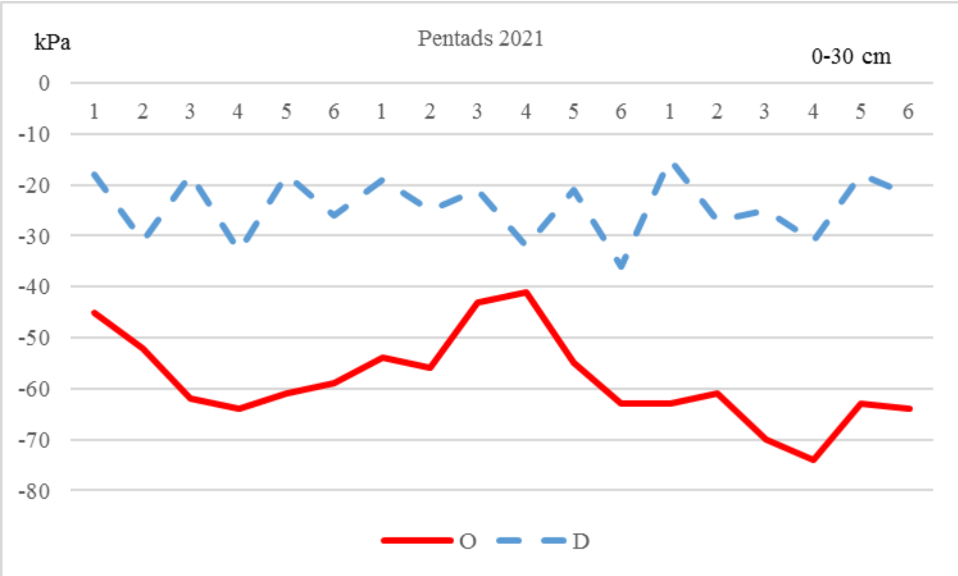


Fig. 8. Soil water potential in kPa for different water variants: O and D, two levels of soil depth: 0-30 cm and 30-60 cm in the year 2020



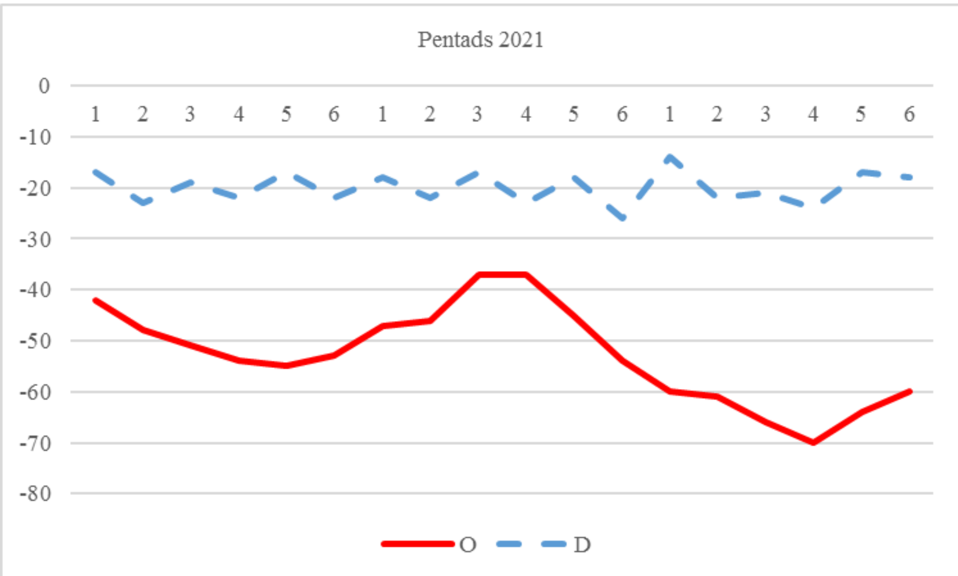


Fig. 9. Soil water potential in kPa for different water variants: O and D, two levels of soil depth: 0-30 cm and 30-60 cm in the year 2021

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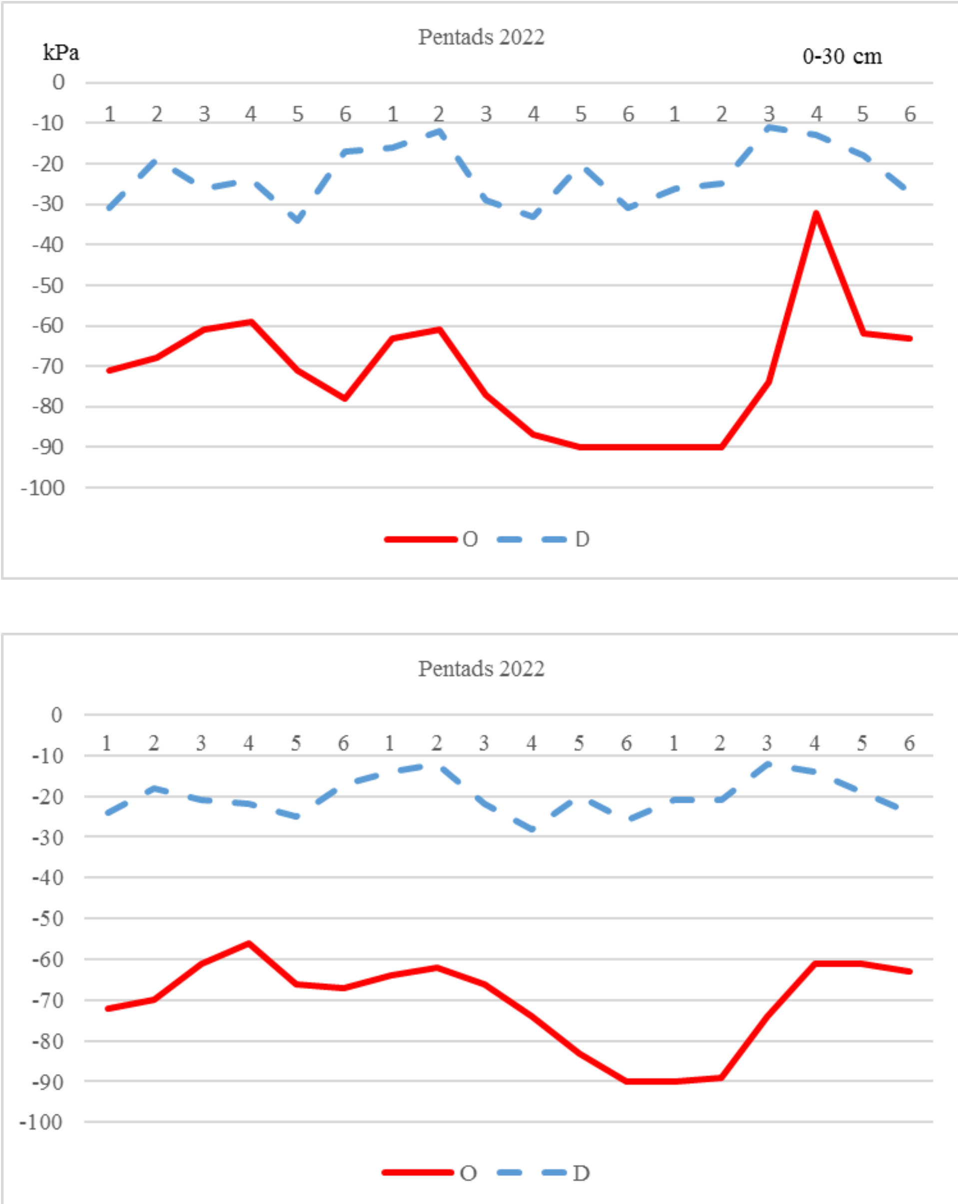

Fig. 10. Soil water potential in kPa for different water variants: O and D, two levels of soil depth: 0-30 cm and 30-60 cm in the year 2022

5.2 WATER NEEDS OF ASPARAGUS

5.2.1. Field water consumption (S)

Daily water consumption values depended primarily on the water treatments used in the experiment (tab. 7). Water consumption in drip-irrigated plots during the irrigation season in individual years was 2.99 mm. The highest water consumption values were recorded in July 2022, when the average daily water consumption exceeded 4 mm. Average daily water consumption in the irrigated plots during the study years increased during the irrigation season, reaching an average of 1.78 mm in June, 3.70 mm in July, and 3.48 mm in August (tab. 7).

At unirrigated plots, where moisture levels depended solely on natural precipitation, daily water consumption varied greatly, depending on rainfall conditions in individual years (tab. 7). Average daily water consumption was 2.02 mm. The highest water consumption was observed in the year with the highest rainfall (2020), reaching 2.07 mm. In most irrigation seasons, a trend of increasing water consumption was observed in June and July, and a decreasing average daily water consumption in August. Average daily water consumption in non-irrigated plots was 1.51 mm, 2.29 mm, and 2.26 mm, in June, July, and August, respectively. Similar trends in field water consumption depending on rainfall were observed by Gilewska et al. [1995] for agricultural plants.

The calculated values and trends in daily water consumption in own experiment are very similar to those obtained by Paschold et al. [2004]. The daily water consumption (ET_c) values obtained under lysimetric conditions in the first year of cultivation for drip-irrigated variants averaged 1.6 mm in June, 2 mm in July, and 3 mm in August. The values obtained for the non-irrigated variants ranged from 1.4 mm (June) to 1.8 mm (August). Pardo et al. [1997] obtained average daily water consumption (ET) values of 4.6 mm day–1 in the 4th and 5th years of asparagus cultivation. Grabarczyk [1976] demonstrated a close correlation between field water consumption and evapotranspiration over the plant canopy ($r = 0.97$) under conditions of optimal soil moisture.

The calculated monthly and annual field water consumption values for the various water treatments are presented in tab. 8. During the study years, water requirements for drip-irrigated plots were 241 mm. Analyzing monthly water consumption values for irrigated plots, it can be concluded that in almost all study years, higher values occurred in July. The exception was 2021, when water consumption was higher in August.

Water consumption at non-irrigated plots fed solely by natural rainfall was characterized by significant fluctuations. Differences in total water consumption between individual years were significant and closely correlated with atmospheric precipitation. The lowest water consumption was recorded in 2021 (153.4 mm), a year characterized by low rainfall. The highest values were recorded in 2020 and 2022, with 156.1 mm and 160 mm, respectively, when the highest rainfall occurred. Average water consumption at non-irrigated sites was approximately 156 mm.

Table 7. Daily water consumption of asparagus plants in irrigation period (VI-VIII) during the experimental years at the moisture-controlled layer

Experimental year	Water variant	Month of the irrigation period			Mean in irrigation season [mm]
		VI	VII	VIII	
2019***	O	1.28*	1.55	0.95	0.92
	D	1.53*	1.66	2.27	1.82
2020	O	1.74**	2.99	1.48	2.07
	D	1.97**	3.62	3.14	2.91
2021	O	1.28**	2.00	2.53	1.94
	D	1.36**	3.32	3.69	2.79
2022	O	1.52**	1.89	2.77	2.06
	D	2.01**	4.18	3.62	3.27
Mean 2020-2022	**O**	**1.51****	**2.29**	**2.26**	**2.02**
	D	**1.78****	**3.70**	**3.48**	**2.99**

An increase in water consumption was observed in the irrigated plots, which averaged 241 mm for the yielding plantation. Paschold et al. [2004] reported that water consumption in the non-yielding plantation and drip-irrigated plots was 91 mm.

The observed trends in large fluctuations in field water consumption at non-irrigated plots confirm earlier studies [e.g., Pacholak 1986]. Żarski [1993] reports that field water consumption at non-irrigated plots is almost equal to atmospheric precipitation. The average field water consumption values in irrigated plots, i.e., under optimal moisture conditions, observed in own experiment were similar to those obtained by Paschold et al. [2001] under similar climatic and soil conditions. Their results indicate that water needs in the period from June 20th to September 1st are 150–241 mm. Similar values were obtained in studies in Poland by Rolbiecki [2013]. Hartmann [1981] estimates water needs depending on rainfall conditions at 179–240 mm. According to Pardo et al. [1997] seasonal water consumption by asparagus plants under lysimetric conditions was 274-294 mm.

In another study by Paschold et al. [2004], water consumption by asparagus plants grown under lysimeter conditions was 266-292 mm in irrigated plots and increased with higher soil moisture levels. In own study also found higher water consumption in drip irrigated plots, where higher irrigation rates were applied. However, under control conditions (no irrigation), field water consumption was closely dependent on rainfall. Significantly higher total water requirements for asparagus grown under different climatic conditions are reported by Cannell and Takatori [1970] for northern California, Robinson et al. [1984], and Roth and Gardner [1989] for Arizona.

Tab. 8. Total water consumption of asparagus plants in irrigation period (VI-VIII) during the experimental years at the moisture-controlled layer

Experimental year	Water variant	Month of the irrigation period			Total water consumption [mm]
		VI	VII	VIII	
2019***	O	38.6*	48.3	29.6	116.5
	D	46.1*	51.5	70.6	168.2
2020	O	17.4**	92.7	46.0	156.1
	D	19.7**	112.4	97.4	229.5
2021	O	12.8**	62.1	78.5	153.4
	D	13.6**	103.1	114.6	231.3
2022	O	15.2**	58.7	86.1	160.0
	D	20.1**	129.6	112.5	262.2
Mean 2020-2022	**O**	**15.1****	**71.2**	**70.2**	**156.5**
	D	**17.8****	**115.0**	**108.2**	**241.0**

O – non irrigated plots
D – drip irrigated plots
* – whole month
** – 3rd decade
*** unyielding plantation

4.1.2.2. Reference evapotrasnspiration (ET_o)

The Hargreaves model modified by Droogers and Allen (ET_o^{HDA}), based on air temperature measurements, was used to calculate reference evapotranspiration (ET_o) during the months of asparagus irrigation (June, July, and August). The mean ET_o values calculated using the Hagreaves-^{DA} formula for the irrigation period were 422.4 mm for the non-yielding plantation (tab. 9) . The highest values of reference evapotranspiration occurred in June and July (140.2 and 146.1 mm), while the lowest ones occurred in August (136.1 mm). The mean value of reference evapotranspiration during the growing season was 338.2 mm for the Hargreaves-^{DA} model (Table 1). The highest values were recorded in July during this period. The average evaporation in the third decade of June during the period of yielding plantation was 53.3 mm, for July 152.4 mm, and for August 132.6 mm.

Table 9. Total reference evapotranspiration (ET_o^{HDA}) in irrigation period (VI-VIII) during the experimental years, calculated by Hargreaves's formula in modiffication of Droogers and Allen

Experimental year	Month of the irrigation period			Total ET_o^{HDA} [mm]
	VI	VII	VIII	
2019	140.2*	146.1	136.1	422.4
2020	48.1**	148.1	133.8	330.0
2021	53.5**	152.5	118.0	324.0
2022	58.2**	156.5	146.0	360.7
Mean 2020-2022	**53.3****	**152.4**	**132.6**	**338.2**

* whole month; ** 3rd decade

The calculated average monthly values of reference evapotranspiration for the years in our own experiment were very similar to the results obtained and presented by Łabędzki et al. [2011] for conditions occurring in Poland, calculated based on the Penman-Monteith formula. The maximum ET_o values in July were 157 mm and in August 123 mm, which is similar to the values calculated using the Hargreaves-^{DA} formula for these months in the years of research. Widmoser [2009] reports that under some meteorological conditions, evapotranspiration determined using the method recommended by FAO and ICID (i.e., Penman-Monteith) may be subject to an error of up to 30% compared to other methods. The ET_o values calculated using the Hargreaves-^{DA} model remained at the level of the maximum Penman-Monteith ET_o values [Łabędzki et al. 2011], which was probably due to the fact that the experiment was located in a region with a high reference evapotranspiration rate and a water balance lower than -200 mm [Koźmiński 1986, Rojek 2001, Łabędzki et al. 2011].

Treder et al. [2010] also obtained similar values of mean daily ET_o to those obtained in own experiment. They also demonstrated a very high correlation between ETo calculated from the Penman-Monteith equation and ETo from the Hargreaves^{DA} formula (r = 0.78). An even higher correlation (r = 0.97) between ETo^{PM} and ETo^{H} was found by Tabari et al. [2011].

The ET_o values obtained in own calculations using the Hargreaves^{DA} model and their high consistency and similarity to the ET_o calculated using the Penman-Monteith formula allow to conclude that it could be used in practice to determine ET_o as an alternative to the complicated Penman-Monteith method. Treder et al. [2010] conclude that, based on a preliminary assessment, the Hargreaves computational model in the Droogers and Allen modification can be used in Polish climatic conditions in the case of limited availability of meteorological data (only T_{min} and T_{max}).

4.1.2.3. Plant coefficients (k_c)

Determining plant water needs in relation to climatic criteria is based on the assumption that water consumption by a plant is determined mainly by meteorological conditions and the plant development stage [Ley et al. 1994; Łabędzki 2006; Sentelhas et al. 2010]. Therefore, to correctly determine the crop evapotranspiration of a given plant (ET_c) using reference evapotranspiration (ET_o), the plant coefficient method (k_c) is used [Łabędzki 1996, 2006; Paschold et al. 2002]. In own research, in order to determine the water needs of asparagus based on climatic criteria, plant coefficients (k_c) were calculated for the Hargreaves ^{DA} model (tab. 10).

The coefficients determined in own experiment were determined for the irrigation period of asparagus summer stalks. For a non-yielding plantation, this period was from the beginning of June to the end of August, while for a yielding plantation – in Polish conditions from the second year of cultivation – this period was from the end of harvest (third decade of June) to the end of August.

For the Hargreaves^{DA} model, the values of plant coefficients calculated for the non-yielding plantation were 0.33 for June, 0.35 for July and 0.52 for August. For the months of the irrigation period of the yielding plantation, the values of k_c coefficients were 0.33 for June, 0.76 for July and 0.82 for August.

Table 10. Plant coefficients k_c for months of irrigation period for calculation of asparagus crop evapotranspiration according to Hargreaves $_{DA}$'s formula

ET_o	Cultivation year	k_c for month of irrigation period		
		VI	VII	VIII
$Hargreaves_{DA}$	1st year	0.33	0.35	0.52
	from 2nd year	0.33	0.76	0.82

The plant coefficients k_c determined for asparagus under optimal humidity conditions for the meteorological conditions of central Poland represent the first attempt to calculate the water needs of asparagus plants based on climatic criteria under organic cultivation. Rolbiecki [2013] previously performed this for conventional crops. A comparison of the determined values of the coefficients of the ET_o calculation model (Hargreaves^{DA}) with the values of the coefficients determined by other authors is presented in tab. 11. The values of the plant coefficients for the various models enabling the calculation of ET_o were slightly higher than those in our calculations for organic cultivation in a non-yielding plantation. For a yielding plantation, the k_c coefficient values were similar to those obtained by other authors. The coefficient values given by Paschold et al. [2002] for ET_o calculated using the Penman-Monteith model were almost the same, which confirms the correctness of the calculation methods used in own study. Small differences in the k_c coefficient values for asparagus were found for ET_o obtained from the Penman-Monteith equation [Battilani 1997, Allen et al. 1998] and that obtained by Doorenbos and Pruitt [Pardo et al. 1997].

Table 11. Crop coefficients k_c for asparagus during the irrigation period

Source	ET_o	Plantation	k_c for stages of development of asparagus summer stalks	
			stage 1	stage 2
Paschold i in. [2002]	Penman--Monteith	*	0.5	0.7 – 0.8
		**	0.6	0.8 – 1.1
Allen i in. [1998]	Penman--Monteith	**	0.5	0.9 – 1.0
Pardo i in. [1997]	Doorenbos i Pruitt	**	0.4	0.9 – 1.1
Battilani [1997]	Penman--Monteith	**	0.6	0.8–1.1

Rolbiecki [2013]	Grabarczyk	*	0.5	0.8 – 0.9
		**	0.5	0.8 – 1.1
	$Hargreaves_{DA}$	*	0.4	0.7 – 0.8
		**	0.5	0.8 – 1.1
Sadan-Ozdemir [2025]	$Hargreaves_{DA}$	*	0.33	0.35 – 0.52
		**	0.33	0.76 – 0.82

* –unyielded plantation
** –yielded plantation

4.1.2.4. Crop evapotranspiration (ET_{cD})

The values of crop evapotranspiration of asparagus calculated based on the climatic criterion, i.e., taking into account the plant coefficient k_c specific to a given plant species and its development stage and the correction factors k_r for surfaces with limited wetting, are presented in tab. 12. The values of the reference evapotranspiration calculated using the $Hargreaves^{DA}$ model were multiplied by the determined k_c coefficients for this formula and k_r proposed by Treder [Treder 2021]. The values of these coefficients are presented in tab. 13. The average crop evapotranspiration of asparagus in the years of yielding plantation was 240 mm on average for the $Hargreaves^{DA}$ model (tab. 12). During the irrigation period, higher average values of crop evapotranspiration of asparagus under optimal moisture conditions (subsurface drip irrigation) were obtained in July.

The obtained ET_{CD} values for asparagus during the irrigation season are similar to the crop evapotranspiration values calculated by Paschold et al. [2001, 2002]. The water requirements of asparagus were 150-241 mm, depending on the growing season. The method of calculating plant water needs using the reduction factor is also recommended by other authors, including Allen et al. [1998], Drupka [1986], Smith [1992], and Rolbiecki [2013].

Table 12. Crop evapotranspiration of asparagus plants in irrigation period (VI – VIII), during the experimental years calculated acc. to $Hargreaves_{DA}$'s formula ($ETc_D^{HDA} = ET_o^{HDA} \cdot k_c^{HDA} \cdot k_r^T$) for limited wetting area (subsurface drip irrigation)

Experimental year	Month of the irrigation period			Total ET_p crop [mm]
	VI	VII	VIII	
2019	13.0*	24.5	46.0	83.5
2020	10.3**	112.6	109.7	232.6
2021	17.6**	115.9	96.8	230.0
2022	19.2**	118.9	119.7	257.8
Mean 2020-2022	**15.7****	**115.8**	**108.7**	**240.0**

* whole month
** 3rd decade

Table 13. Correction coefficients k_r acc. Treder for months of irrigation period, to computing crop evapotranspiration for asparagus at the limited wetting area (subsurface drip irrigation) – own preparation

Coefficients	Cultivation year	k_r for month of irrigation period		
		VI	VII	VIII
Treder's coefficient	1st year	0.28	0.48	0.65
	from 2nd year	0.65	1	1

Crop evapotranspiration values for asparagus, based on the k_c and k_r coefficients determined in own experiment, allow to conclude that the methodology used and the calculations performed are correct. This is also confirmed by the established relationships between the calculated ET_c and field water consumption. The calculated values of water requirements for asparagus in the treatments with limited wetting area were consistent with field water consumption (tab. 14). They amounted to 0.618 in July and 0.184 in August, respectively. The correlation coefficient value for July was significant. The correlation coefficient was significant for the significance level $\alpha = 0.05$.

Table 14. Correlation coefficients (r) between field water consumption on drip irrigated plots (S_D) and crop evapotranspiration calculated by the Hargreaves$_{DA}$ ($ET_{pK}^{HDA} = ET_o^{HDA} \cdot k_c^{HDA} \cdot k_r^T$) formula in months VII and VIII for limited wetting area (subsurface drip irrigation)

Specification	S_D	
	VII	VIII
$Et_o^{HDA} \cdot k_c^{HDA} \cdot k_r^T$ (Et_{cD}^{HDA})	0.618*	0.184*

S_D Field water consumption at drip irrigated plots; * – $\alpha = 0.05$

5.3. THE EFFECT OF DRIP IRRIGATION ON SUMMER STALK PARAMETERS

Drip irrigation used after harvest in the next growing season before asparagus harvest, irrigated plots (D) produced taller stalks (218 cm on average) than non-irrigated plots (O), which averaged 186 cm significantly increased the average of the years (tab. 15). Among the cultivars, 'Cumulus', 'Bacchus', and 'Mondeo' under irrigation reached the highest mean stalk height (221 cm), while 'Mondeo' showed the lowest performance under non-irrigated conditions (182 cm). The interaction between irrigation and cultivar was not significant, indicating that all cultivars responded similarly to irrigation in terms of stalk height. The effect of irrigation on the height of summer stalks was statistically significant in all years ($p < 0.05$). A statistically proven influence of irrigation on the height of asparagus summer stalks and a study conducted in Poland found that drip irrigation increased the postharvest summer shoot length by an average of 20 cm

(13%) in the year preceding harvest was also demonstrated by other authors [Pashold et al. 2004; Rolbiecki et al 2021; Rolbiecki 2024].

Table 15. Height of summer stalks of asparagus chosen cultivars in years of research

Irrigation	Cultivar	Studied year				Mean
		2019	2020	2021	2022	
O	Cumulus	161.0	191.0	195.0	197.0	186.0
	Bacchus	162.0	201.0	200.0	198.0	190.0
	Gijnlim	176.0	191.0	185.0	195.0	187.0
	Mondeo	154.0	201.0	185.0	188.0	182.0
	Mean	**163.0**	**196.0**	**191.0**	**194.0**	**186.0**
D	Cumulus	212.0	231.0	230.0	212.0	221.0
	Bacchus	209.0	211.0	235.0	228.0	221.0
	Gijnlim	211.0	195.0	208.0	224.0	209.0
	Mondeo	200.0	235.0	226.0	223.0	221.0
	Mean	**208.0**	**218.0**	**225.0**	**222.0**	**218.0**
LSD $_{0.05}$						
Irrigation (I)		11.321	6.915	10.662	11.873	9.964
Cultivar (II)		4.443	5.888	4.551	3.651	3.555
Interaction (IxII)		ns	ns	ns	ns	ns
Interaction (IIxI)		ns	ns	ns	ns	ns

The diameter of summer stalks was significantly affected by both irrigation and cultivar ($p < 0.05$) (tab. 16). Irrigated plots produced thicker stalks (19 mm) compared to non-irrigated ones (15 mm). ‘Gijnlim’ and ‘Cumulus’ had the highest average diameter (20 mm) under irrigation, while ‘Bacchus’ and ‘Gijnlim’ had the lowest (14 mm) in non-irrigated conditions. No significant interaction was observed between irrigation and cultivar, indicating consistent irrigation effects across cultivars. Other studies showed same results as; Knaflewski et al. [2014) reported that there was a positive correlation between the yield in the next vegetation period and the plant growth index of the tested asparagus varieties, and irrigation had a positive effect on the diameter and length of summer shoots. In the study published by Rolbiecki et al. (2024), drip irrigation method caused a significant effect on the diameter of summer stems of asparagus varieties grown in light sandy soil and showed an increase of approximately %25.6, i.e. 2.56 mm. Huang C. et al (2022) showed that reduced water amount caused a decrease in the stem diameter of maize plants and negatively affected the yield.

Table 16. Diameter of summer stalks of asparagus chosen cultivars in years of research

Irrigation	Cultivar	Studied year				Mean
		2019	2020	2021	2022	
O	Cumulus	16	15	16	15	15
	Bacchus	14	15	14	14	14
	Gijnlim	15	16	14	14	15
	Mondeo	16	15	15	15	15
	Mean	**15**	**15**	**15**	**14**	**15**
	Cumulus	17	16	24	24	20

D	Bacchus	19	16	20	18	18
	Gijnlim	20	18	19	19	19
	Mondeo	17	21	20	21	20
	Mean	**18**	**18**	**21**	**20**	**19**
LSD $_{0.05}$ Irrigation (I) Cultivar (II) Interaction (IxII) Interaction (IIxI)		 1.522 1.111 ns ns	 1.641 0.462 ns ns	 2.541 1.367 ns ns	 1.871 0.221 ns ns	 1.721 0.842 ns ns

Irrigation significantly increased the number of summer stalks across all cultivars and years ($p < 0.05$) (tab. 17). The average number of stalks under irrigation was 4, compared to 3 in non-irrigated conditions. ‘Gijnlim’ exhibited the highest mean number of stalks (4) under irrigation, while ‘Cumulus’ had the lowest number (2) under non-irrigated conditions. Again, the interaction effect between irrigation and cultivar was not significant, suggesting a uniform response pattern to irrigation across all cultivars. As a result of the study we conducted in Poland in 2024, of which I was a co-author, it was found that drip irrigation in the post-harvest period significantly increased the number of summer stalks [Rolbiecki et al. 2024]. As a result of the study conducted by Byl [2013], it was shown that the drip and sprinkler irrigation methods he tested were quite effective on asparagus stems and yield. Paschold et. al [2004] also showed that drip irrigation increased the number of summer stalks.

Table 17. Number of summer stalks of asparagus chosen cultivars in years of research

Irrigation	Cultivar	Studied year				Mean
		2019	2020	2021	2022	
O	Cumulus	16	15	16	15	15
	Bacchus	14	15	14	14	14
	Gijnlim	15	16	14	14	15
	Mondeo	16	15	15	15	15
	Mean	**15**	**15**	**15**	**14**	**15**
D	Cumulus	17	16	24	24	20
	Bacchus	19	16	20	18	18
	Gijnlim	20	18	19	19	19
	Mondeo	17	21	20	21	20
	Mean	**18**	**18**	**21**	**20**	**19**
LSD $_{0.05}$ Irrigation (I) Cultivar (II) Interaction (IxII) Interaction (IIxI)		 1.522 1.111 ns ns	 1.641 0.462 ns ns	 2.541 1.367 ns ns	 1.871 0.221 ns ns	 1.721 0.842 ns ns

Drip irrigation applied after harvest and before the next asparagus harvest had a significant impact on the weight of summer stalks (tab. 18). Under irrigated conditions, ‘Gijnlim’ recorded the highest average yield at 4.02 kg, followed by ‘Mondeo’ with 3.70 kg, ‘Bacchus’ with 3.44 kg, and ‘Cumulus’ with the lowest at 3.16 kg. In non-irrigated conditions, ‘Mondeo’ still led with 2.81 kg, followed by ‘Bacchus’ at 2.65 kg, ‘Gijnlim’ at 2.45 kg, and ‘Cumulus’ again at the bottom with 2.17 kg. These results indicate that ‘Gijnlim’ and ‘Mondeo’ respond most positively to irrigation, while ‘Cumulus’ consistently shows the lowest performance regardless of water availability. A study conducted in the USA investigated the effects of irrigation amount and management on summer stalks and found that irrigation increased the number and weight of summer stalks Drost [2002]. In a study conducted in Poland, irrigation was found to have a positive effect on both summer shoots and green spears [Rolbiecki 2024]. Warner at al. [2018] found that irrigation effected the weight of summer stalks in studied cultivars.

Table 18. Weight of summer stalks of asparagus chosen cultivars in years of research

Irrigation	Cultivar	Studied year				Mean
		2019	2020	2021	2022	
O	Cumulus	1.96	2.11	2.21	2.40	2.17
	Bacchus	2.45	2.52	2.71	2.93	2.65
	Gijnlim	2.11	2.45	2.55	2.68	2.45
	Mondeo	2.77	2.80	2.75	2.91	2.81
	Mean	**2.32**	**2.47**	**2.55**	**2.73**	**2.52**
D	Cumulus	2.97	3.21	3.10	3.35	3.16
	Bacchus	3.29	3.35	3.52	3.61	3.44
	Gijnlim	3.36	4.21	4.43	4.10	4.02
	Mondeo	3.24	3.68	3.88	4.01	3.70
	Mean	**3.21**	**3.61**	**3.73**	**3.77**	**3.58**
LSD $_{0.05}$						
Irrigation (I)		0.431	0.333	0.621	0.872	0.452
Cultivar (II)		0.233	0.211	0.190	0.321	0.275
Interaction (IxII)		0.342	0.121	0.108	0.217	0.190
Interaction (IIxI)		0.321	0.134	0.261	0.177	0.231

5.4. TOTAL MARKETABLE YIELD DETERMINATION

Postharvest drip irrigation treatment of asparagus plants used in the growing season preceding the asparagus harvest significantly increased green spear yields from 3.92 t·ha^{-1} to 5.34 t·ha^{-1} in the studied years (tab. 19). The highest marketable yield increase under drip irrigation— on average, for 4 years of research—were obtained for ‘Cumulus’ with 6.98 t ha^{-1} and 5.52 t. ha^{-1} Bacchus cultivars. The lowest yields under drip irrigation (under 5 t.ha^{-1}) were collected from Gijnlim and Mondeo cultivars.The best response to drip irrigation was noted in Cumulus cultivar from the total studied years and lowest was collected from the Mondeo cultivar.

Table 19. Marketable yield (t ha⁻¹) of asparagus green spears of chosen cultivars in years of research (own preparation)

Irrigation	Cultivar	Studied year 2020	2021	2022	2023	Mean
O	Cumulus	2.30	4.96	5.22	6.35	4.70
	Bacchus	1.95	4.80	4.93	6.11	4.44
	Gijnlim	1.80	4.02	4.20	5.27	3.82
	Mondeo	1.50	2.85	2.95	3.60	2.72
	Mean	**1.88**	**4,15**	**4.32**	**5.33**	**3.92**
D	Cumulus	3.90	6.95	7.35	9.74	6.98
	Bacchus	2.85	5.90	6.21	7.15	5.52
	Gijnlim	2.98	5.10	5.43	6.36	4.96
	Mondeo	2.50	3.80	3.98	5.33	3.90
	Mean	**3.06**	**5.43**	**5.74**	**7.15**	**5.34**
LSD $_{0.05}$						
Irrigation (I)		0.337	0.601	0.878	0.553	0.651
Cultivar (II)		0.293	0.339	0.491	0.213	0.165
Interaction (IxII)		0.341	0.451	0.331	0.621	0.342
Interaction (IIxI)		0.258	0.275	0.453	0.198	0.267

Brainerd et al. [2012; 2017] reported similar yields of 31.56 t ha⁻¹ and 32.22 t ha⁻¹ for unirrigated and subsurface drip-irrigated plots. In our experiment, we observed significantly higher yields with drip irrigation, reaching 53 t ha⁻¹ for 'Ravel' compared to the control group. These findings support the idea that irrigation increases yield even under drought conditions and positively affects asparagus growth [Campi et al. 2019; Rolbiecki et al. 2021]. These findings emphasize the importance of irrigation on yield in both our experiment and previous studies.

Drip irrigation, used after the harvest in the next growing season preceding the asparagus harvest, significantly increased the mean spear weight from 38.23 g in the first year 2020 to 44.19 g in 2023 (tab. 20). The mean spear weight due to drip irrigation increased for the studied cultivars and 4 years of research, on average, by 41.54 g, respectively. The greatest mean spear weight under drip irrigation— on average, for 4 years of research—was obtained for the cultivars Mondeo (42.69), Gyjnlim (41.94), Bacchus (41.07). The best response to drip irrigation, with reference to this characteristic, was noted in Mondeo and lowest one was in Cumulus cultivar. According to the results obtained in our study, the drip irrigation system was effective on asparagus plants and had a positive effect on the increase in single spear weight.

Table 20. Single spear weight (g) of asparagus chosen cultivars in years of research

Irrigation	Cultivar	Studied year 2020	2021	2022	2023	Mean
O	Cumulus	34.57	32.21	34.30	33.52	33.65
	Bacchus	31.43	33.08	32.25	31.79	32.13
	Gijnlim	34.80	34.80	33.50	32.23	33.83
	Mondeo	31.43	33.08	32.33	33.45	32.57
	Mean	**33.05**	**33.47**	**33.09**	**32.74**	**33.04**

D	Cumulus	37.27	38.65	40.31	45.72	40.48
	Bacchus	37.14	39.29	44.10	43.76	41.07
	Gijnlim	39.89	42.90	44.31	40.67	41.94
	Mondeo	38.65	40.21	45.26	46.64	42.69
	Mean	**38.23**	**40.26**	**43.49**	**44.19**	**41.54**
LSD 0.05						
Irrigation (I)		0.901	3.555	2.888	4.654	2.993
Cultivar (II)		4.442	5.211	6.414	2.888	1.678
Interaction (IxII)		5.331	4.771	1.015	3.210	2.742
Interaction (IIxI)		4.887	3.887	3.868	2.145	1.098

Rolbiecki et al.'s study [2022] obtained similar results and reported that the subsurface drip irrigation method increased the single spear weight from 41.13 g to 49.36 g and the 'Ramada' variety reached 53.04 g.
As a result of a similar study, Brainard et al. (2018) observed that the irrigation method had a positive effect on the number of spears and yield, but the season and varieties affected the results.

Fontes and Grijalva [2000] emphasized that drip irrigation increased spear biomass and the importance of efficient water management. As a result, it shows that using water at the optimum level and balancing it in accordance with environmental conditions can improve spear development. In another study conducted in Poland between 2006 and 2008, drip irrigation had positive effects on selected asparagus varieties and the average single shoot weight increased from 35.33 g to 40.35 g (14%) [Rolbiecki et al. 2008].

Table 21. Number of spears per single plant (pcs/plant) of asparagus chosen cultivars in years of research

Irrigation	Cultivar	Studied year				Mean
		2020	2021	2022	2023	
O	Cumulus	8.37	7.22	8.51	8.45	8.14
	Bacchus	5.97	6.41	6.19	7.21	6.44
	Gijnlim	5.56	5.89	6.45	6.67	6.14
	Mondeo	6.94	6.50	6.72	6.88	6.76
	Mean	**6.71**	**6.50**	**6.96**	**7.30**	**6.87**
D	Cumulus	12.27	11.37	11.82	12.42	11.97
	Bacchus	9.22	8.99	9.67	10.11	9.49
	Gijnlim	9.09	9.67	10.32	10.77	9.96
	Mondeo	9.32	10.01	9.77	9.89	9.74
	Mean	**9.97**	**10.01**	**10.39**	**10.79**	**10.29**
LSD 0.05						
Irrigation (I)		0.960	0.845	0.888	1.543	0.396
Cultivar (II)		1.476	1.117	1.111	1.264	1.508
Interaction (IxII)		2.087	1.885	1.765	1.165	0.231
Interaction (IIxI)		1.362	0.967	0.456	0.564	0.342

Drip irrigation, applied after the harvest in the growing season preceding the next asparagus harvest significantly increased the number of green spears per plant from 9.97 in the first year of study to 10.79 last year (tab. 21). Green spears number per plant increased due to drip irrigation for the studied cultivars and 4 years of research, on average, by 10.29 pcs. The highest increase in green spears number per plant (11 or more) under drip irrigation conditions, on average, for 4 years of research, was observed for the cultivar Cumulus (11.97), the lowest was Bacchus (9.49) cultivars.

As a result of the research, it was determined that the use of drip irrigation was effective in increasing the number of asparagus spears. This is also supported by previous studies of other authors. Rolbiecki et al. [2024] reported that the number of green spears per plant increased on average due to drip irrigation in the varieties examined and in the two-year study. Zinkernagel et al. [2018] reported that the ‘Gijnlim’ and ‘Jersey Deluxe’, responded positively to irrigation. In addition, irrigation was effective on the quality protection of asparagus spears against heat stress in ‘Guelph Millennium’ [Brainard et al. 2018].

5.5. TOTAL ANTHOCYANINS DETERMINATION

Anthocyanins are a group of plant pigments classified as natural non-nutritive substances (NNS). These are polyphenolic glycosidic compounds found in plants. These pigments have been identified in all parts of plants, namely flowers, fruits, leaves, stems, as well as roots and wood. In cells, they are located in vacuoles [Piątkowska et al. 2011]. The health-promoting properties of anthocyanins lie in their antioxidant, anti-inflammatory, and anticancer effects, neutralizing free radicals. These compounds support circulatory health, improve visual function, support the nervous system, and positively influence glucose regulation and insulin resistance [Mazza 2007; Mattioli et al. 2020]. These are compounds of potential importance in plant responses to stress [Steyn et al. 2002; Landi et al. 2012]. According to Mol et al. [1996], the biosynthesis of these biologically active substances is regulated by environmental factors such as temperature, soil moisture, and light.

Table 22. The content of total anthocyanins, [$mg \cdot kg^{-1}$ f.w.] of asparagus green spears cultivars in years of research.

Irrigation	Cultivar	Studied year				Mean
		2020	2021	2022	2023	
O	Cumulus	5.67	7.33	8.00	9.33	7.58
	Bacchus	6.67	7.00	5.67	9.00	7.08
	Gyjnlim	9.00	5.67	4.67	9.33	7.17
	Mondeo	7.00	9.33	6.67	8.67	7.92
	Mean	**7.08**	**7.33**	**6.25**	**9.08**	**7.43**
D	Cumulus	3.00	7.33	4.67	8.67	5.92
	Bacchus	4.00	5.00	4.67	7.67	5.33
	Gyjnlim	4.00	7.33	7.00	3.67	5.50
	Mondeo	5.67	8.00	6.67	5.00	6.33
	Mean	**4.16**	**6.91**	**5.75**	**6.25**	**5.77**

LSD $_{0.05}$					
Irrigation (I)	2.096	ns	ns	1.455	0.872
Cultivar (II)	ns	ns	ns	ns	ns
Interaction (IxII)	ns	ns	ns	ns	ns
Interaction (IIxI)	ns	ns	ns	ns	ns

In this result of the study, it was seen that the selected cultivars and the drip irrigation factor did not have much effect in the evaluated years (tab. 22). After comparing the control factor to drip irrigation, it was determined that the cultivars in the control section obtained higher results. While the control section obtained 7.43 (mg·kg^{-1} f.w.) in total, it was determined as 5.77 (mg·kg^{-1} f.w.) in the drip irrigation factor (Table 2). In both factors (control and drip irrigation), the highest result was determined from Mondeo while the lowest result was determined in the Bacchus cultivar. The results obtained in this experiment are consistent with the literature, because, as reported by Steyn et al. (2002), Janská et al. [2010] and Landi et al. [2012] anthocyanins accumulate in plants under the influence of various abiotic stresses, such as drought, salt stress, UV stress, strong light, and high temperature. Similar to this study, a study was conducted by Zhang et al. [2024] and examined the responses of drought-tolerant on different asparagus varieties under water stress. As a result of the analyses, anthocyanin levels were not measured at a significantly. Liang et al. [2022] also reported that temperature negatively affected anthocyanin accumulation in purple asparagus stems and caused discoloration. As a result, it was reported that environmental factors were effective in anthocyanin synthesis in asparagus.

5.6. TOTAL CHLOROPHYLL AND CAROTENOIDS CONCENTRATION

Both irrigation and the cultivar influenced the growth of the tested compound. Drip irrigation significantly effected on average for 4 years of studied cultivars with total 111.51 mg·kg-1·f.w.. The Mondeo cultivar contained significantly the most total chlorophyll (121.74 mg·kg-1·f.w.), and the Gyjnlim cultivar contained significantly the least (97.19 mg·kg-1 f.w.). This cultivar is usually grown for whitened spears, while the color of the spears in the light may change to light green, which was obtained in tests. Irrigation caused a significant increase in the tested compound in the spears (tab. 23). The analysis of total carotenoid content in green asparagus spears across different cultivars and irrigation regimes over four years revealed that both cultivar and year had statistically significant effects, while irrigation and their interactions were not significant (tab. 24). Among the cultivars, ‘Gyjlim’ consistently showed the highest mean carotenoid content (61.07 mg·kg^{-1} f.w.), regardless of irrigation regime. In general, the year 2023 showed increased carotenoid accumulation across most cultivars. Interestingly, certain cultivars such as 'Bacchus' and 'Mondeo' exhibited higher carotenoid levels under non-irrigated (D) conditions, suggesting a potential increase in secondary metabolite production under mild water stress. Although the average carotenoid content was slightly higher in the non-irrigated group (55.48 mg·kg^{-1}f.w.) compared to the irrigated one (50.69 mg·kg^{-1} f.w.), this difference was not statistically significant, indicating that irrigation had no decisive influence on carotenoid accumulation. Bioactive compounds in plants, such as vitamin C, carotenoids and polyphenols, are effective on antioxidant activity [Maeda et al. 2005].

The physiological response of plants to drip irrigation assessed by determining the concentration of assimilation pigments (chlorophyll a + b, carotenoids) in asparagus spears. Assimilation pigments, which include chlorophyll a, b, and carotenoids, are the most important assimilation pigments in plants, affecting plant photosynthetic intensity and biomass production [Devlin and Barker 1971; Karczmarczyk et al. 1993]. According Yan et. al [2024] drought stress affects photosynthetic pigments, reducing the net rate of plant photosynthesis and the energy produced by photosynthetic pigments. The main photosynthetic pigment, which enables photochemical reactions, is chlorophyll a molecules located in the centers of the PSI and PSII photosystems. The accessory pigments in the photosynthetic process are chlorophyll b and carotenoids (carotenes and xanthophylls), also called antenna pigments. Carotenoids also play a protective role in photosynthesis by dissipating excess energy supplied to the photosystem centers as heat [Collins 2001; Biczak et al. 2016]. They also play a regulatory role in cell differentiation, growth, and metabolism, as well as a structural role by stabilizing thylakoid membranes in plants [Collins 2001]. The most important characteristic of these pigments is their antioxidant activity against reactive oxygen species and free radicals. Thanks to this property, they protect the body against many serious, chronic diseases. Frequent dietary intake of foods rich in these compounds effectively counteracts the development of cancer and atherosclerosis [McQuistan et al. 2012; Obana 2025; Yang et al. 2025].

Table 23. Total Chlorophyll concentration [mg·kg^{-1} f.w.] of asparagus green spears cultivars in years of research (own preparation).

Irrigation	Cultivar	Studied year				Mean
		2020	2021	2022	2023	
O	Cumulus	61.97	83.57	55.33	54.57	63.86
	Bacchus	77.17	68.27	59.77	114.03	79.81
	Gyjnlim	75.67	83.70	86.47	123.67	92.38
	Mondeo	74.00	71.97	67.13	60.83	68.48
	Mean	**72.20**	**76.87**	**67.17**	**88.27**	**76.13**
D	Cumulus	94.27	120.80	82.93	143.20	110.30
	Bacchus	100.37	121.13	103.70	142.03	116.81
	Gyjnlim	77.13	84.07	77.13	150.43	97.19
	Mondeo	130.03	97.13	132.03	127.77	121.74

	Mean	**100.45**	**105.78**	**98.94**	**140.85**	**111.51**
LSD $_{0.05}$ Irrigation (I) Cultivar (II) Interaction (IxII) Interaction (IIxI)		 **23.995** ns ns ns	 **22.542** ns ns ns	 **27.629** ns ns ns	 **27.868** **ns** ns ns	 **11.930** ns **30.664** **11.613**

ns – non-significant

Table 24. The content of total carotenoids, [mg·kg^{-1} f.w.] of asparagus green spears cultivars in years of research (own preparation)

Irrigation	Cultivar	Studied year				Mean
		2020	2021	2022	2023	
O	Cumulus	47.40	37.90	33.93	56.20	43.86
	Bacchus	50.77	44.37	31.17	56.83	45.78
	Gyjnlim	50.17	64.17	60.23	69.70	61.07
	Mondeo	54.40	44.60	36.43	59.47	48.73
	Mean	50.69	47.76	40.44	60.55	49.86
D	Cumulus	39.50	56.93	51.83	51.17	49.86
	Bacchus	62.90	39.77	42.87	70.27	53.95
	Gyjnlim	53.03	60.57	67.83	62.60	61.01
	Mondeo	66.47	44.74	51.17	46.47	52.21
	Mean	55.48	50.50	53.43	57.63	54.26
LSD $_{0.05}$ Irrigation (I) Cultivar (II) Interaction (IxII) Interaction (IIxI)		 ns ns ns ns	 ns **ns** ns ns	 **7.060** **13.533** ns ns	 ns **ns** ns ns	 ns **11.605** **ns** **ns**

According to Ashraf and Harris [2013], chlorophyll and carotenoids are indicators of stress in plants caused by environmental factors, therefore lower concentrations of these compounds indicate stress caused by lack of hydration. Rolbiecki [2024] reported both the applied irrigation and the cultivar factor as well as the interaction of both factors significantly influenced the content of chlorophyll and total carotenoids in asparagus spears (tab. 24). In research Kermani et al. [2024] reported that total leaf chlorophyll content decreased at different levels of water stress.

5.7. TOTAL DRY MATTER CONTENT

It was observed that the dry matter content measured in green asparagus spears was not significantly dependent on irrigation or cumulus. It was determined that the dry matter level in spears collected from drip-irrigated plants was lower than the non-irrigated control. When compared with the drip-irrigated control group, a total of 7.16% dry matter was obtained in the total of the determined years and a total of 6.67% dry matter was obtained in the drip-irrigated group (tab. 25). In both groups, the highest result was observed in the Cumulus variety and the lowest result was observed in the Bacchus variety As a result, according to the data we obtained, irrigation had no effect on the dry matter content of asparagus plants. In the study by Wichrowska et al. [2018], a similar amount of dry matter was obtained in white asparagus spears plants irrigated with micro-sprinklers and plants of the "Ramos" and "Vulkan" cultivars, 6.63 and 6.42%, respectively, while in the shoots of the "Gijnlim" cultivar the level of dry matter (6.04%) was significantly lower than in the shoots of the "Ramos" cultivar.

Table 25. Total dry matter content (%) in green asparagus spears cultivars in years of research (own preparation)

Irrigation	Cultivar	Studied year				Mean
		2020	2021	2022	2023	
O	Cumulus	7.27	7.13	7.33	7.33	7.27
	Bacchus	7.13	6.27	7.07	6.80	6.82
	Gyjnlim	7.53	6.33	7.60	7.73	7.30
	Mondeo	7,40	6.47	7.53	7.63	7.26
	Mean	**7.33**	**6.55**	**7.38**	**7.37**	**7.16**
D	Cumulus	7.60	6.00	6.87	7.13	6.90
	Bacchus	7.60	6.00	6.53	5.53	6.42
	Gyjnlim	6.93	6.73	6.60	6.73	6.75
	Mondeo	7.20	6.07	6.53	6.60	6.60
	Mean	**7.33**	**6.20**	**6.63**	**6.50**	**6.67**
$LSD_{0.05}$						
Irrigation (I)		**ns**	**0.242**	**0.592**	**0.511**	**0.222**
Cultivar (II)		**ns**	**0.464**	**ns**	**0.979**	**0.396**
Interaction (IxII)		**ns**	**0.484**	**ns**	**ns**	**ns**
Interaction (IIxI)		**ns**	**0.656**	**ns**	**ns**	**ns**

5.8. TOTAL ASH CONTENTS (% DRY MATTER)

The mineral content of asparagus spears, expressed as a percentage of dry matter, ranged between 10.15% and 10.62% across the years and cultivars studied (tab. 26). Statistical analysis revealed a significant effect of the irrigation factor ($p < 0.05$), while the effects of cultivar and interactions were not significant. Non-irrigated (D) conditions generally led to higher mineral content, with a mean value of 10.62%, compared to 10.15% under irrigated conditions (O). This finding indicates that water stress may contribute to a relative increase in mineral concentration in the spears. Although no significant differences were found between cultivars, 'Gyjlim' and 'Mondeo' tended to have slightly higher mineral content on average.

As a result of the study reported by Wichrowska et al. [2018], it was seen that drip irrigation method significantly increased the dry matter and potassium content and decreased the nitrate level in the varieties tested in light soil. Ash content varies depending on the plant organ and species. For comparison: energy willow in biomass contains 0.3–10.8% of ash, virginia mallow 2.2–4.5%, miscanthus 1.6–5.1%, sorghum 6.6–44.4%, cobs 1.9–21%, rapeseed straw 4.0–10.2% [Jagustyn et al. 2011]. The content may be influenced by the mineral content of the soil [Figas 2020].

Table 26. Total ash contents (% dry matter) in green asparagus spears in years of research (own preparation)

Irrigation	Cultivar	Studied year				Mean
		2020	2021	2022	2023	
O	Cumulus	10.09	10.33	10.43	10.26	10.28
	Bacchus	10.04	10.03	10.09	9.93	10.02
	Gyjnlim	10.38	9.5	10.42	10.42	10.24
	Mondeo	10.07	10.27	10.90	10.20	10.36
	Mean	**10.15**	**10.10**	**10.46**	**10.20**	**10.15**
D	Cumulus	10.77	10.53	10.43	10.27	10.50
	Bacchus	10.50	10.60	10.10	10.13	10.33
	Gyjnlim	10.63	10.29	10.29	10.33	10.39
	Mondeo	10.59	9.83	10.37	10.40	10.30
	Mean	**10.62**	**10.31**	**10.30**	**10.28**	**10.62**
LSD $_{0.05}$						
Irrigation (I)		**0.440**	**ns**	ns	**ns**	**ns**
Cultivar (II)		ns	**ns**	**ns**	**ns**	ns
Interaction (IxII)		ns	ns	ns	ns	**ns**
Interaction (IIxI)		ns	ns	ns	ns	**ns**

5.9. ESTIMATION OF THE CHOSEN ELEMENT CONTENT

Potassium (K), a macroelement essential for proper plant growth and development, is the one absorbed by plants in the largest quantities of all cations. Potassium's primary functions include maintaining cell osmotic potential and activating enzymes that play a key role in metabolic processes such as photosynthesis, stomatal motility, ion uptake from soil, carbohydrate, protein, and fat synthesis, and the accumulation of organic compounds in storage organs. Adequate potassium supply increases the efficiency of other nutrient utilization and, in particular, promotes nitrogen uptake by plants. Besides its impact on growth and development, this element also increases plant resistance to disease [Gaj 2013, Grzebisz et al. 2013, Szczepaniak et al. 2014, Figas 2020].

The experimental factors examined did not differentiate the K content in the dry matter of asparagus green spears cultivars in the study years (tab. 27). The

potassium content in the drip-irrigated and non-irrigated plots was similar on average for the study years and amounted to 28.2 g·kg^{-1} d.m. and 27.9 g·kg^{-1} d.m., respectively. Among the studied varieties, the highest K content was determined in the Gyjnlim variety of spears (29.85 g·kg^{-1} d.m.).
According to Gaj [2013], the dynamics of nutrient uptake by plants depends on many factors, namely the species, variety, rate of biomass growth during the growing season, and the supply of plants with other nutrients.

Table 27. The content of K [g·kg^{-1} dm.] of asparagus green spears cultivars in years of research (own preparation)

Irrigation	Cultivar	Studied year 2020	2021	2022	2023	Mean
0	Cumulus	24.5	23.5	30.1	29.2	**26.8**
	Bacchus	25.1	25.6	25.4	24.3	**25.1**
	Gyjnlim	29.2	30.2	32.5	30.2	**30.5**
	Mondeo	29.4	28.3	32.4	27.1	**29,3**
	Mean	**27.1**	**26.9**	**30.1**	**27.7**	**27.9**
D	Cumulus	24.0	22.0	29.7	29.1	**26.2**
	Bacchus	27.4	26.9	29.1	30.4	**28.5**
	Gyjnlim	28.7	25.9	30.6	31.4	**29.2**
	Mondeo	28.4	26.9	33.7	27.1	**29.0**
	Mean	**27.1**	**25.4**	**30.8**	**29.5**	**28.2**
LSD $_{0.05}$						
Irrigation (I)		ns	ns	ns	ns	ns
Cultivar (II)		ns	ns	ns	ns	ns
Interaction (IxII)		ns	ns	ns	ns	ns
Interaction (IIxI)		ns	ns	ns	ns	ns

Magnesium (Mg) occupies a central position in the porphyrin molecule of chlorophyll and influences the proper course of photosynthesis [Verbruggen and Hermans 2013, Ceylan et al. 2016, Tatagiba et al. 2016, Tränkner et al. 2016]. Mg is an activator of many enzymes, such as phosphatases, kinases, ATPases, and carboxylases [Verbruggen and Hermans 2013]. By activating phosphorylation enzymes, whose function is to convert and store energy, magnesium also plays a crucial role in respiration and the accumulation of carbohydrates, proteins, and fats in plants. This element also participates in the regulation of pH in the cell and plays a significant role in protein biosynthesis. It also activates RNA polymerase, thus participating in RNA synthesis in the nucleus [Cakmak and Kirkby 2008, Grzebisz et al. 2010].

In the research no differences were found between the experimental factors used. There were also no interactions between experimental factors influencing the Mg content in dry matter of asparagus green spear over the years of research (tab. 28).

Table 28 . The content of Mg [g·kg-1 dm] of asparagus green spears cultivars in years of research (own preparation)

Irrigation	Cultivar	Studied year 2020	2021	2022	2023	Mean
O	Cumulus	1.24	1.59	1.7	1.75	**1.57**
	Bacchus	1.52	1.61	1.28	1.37	**1.45**
	Gyjnlim	1.38	1.36	1.45	1.50	**1.42**
	Mondeo	1.59	1.69	1.55	1.61	**1.61**
	Mean	**1.43**	**1.56**	**1.50**	**1.56**	**1.51**
D	Cumulus	1.19	1.38	1.48	1.52	**1.39**
	Bacchus	1.35	1.26	1.16	1.28	**1.26**
	Gyjnlim	1.52	1.40	1.49	1.63	**1.51**
	Mondeo	1.32	1.12	1.39	1.44	**1.32**
	Mean	**1.35**	**1.29**	**1.38**	**1.47**	**1.38**
LSD $_{0.05}$						
Irrigation (I)		ns	ns	ns	ns	ns
Cultivar (II)		ns	ns	ns	ns	ns
Interaction (IxII)		ns	ns	ns	ns	ns
Interaction (IIxI)		ns	ns	ns	ns	ns

Calcium (Ca) in plants regulates the activity of many enzymes, including ATPase, phospholipase, and amylase. By combining with sugars, such as pectin, it forms calcium pectinates, which contribute to cell wall stability. This element also stabilizes cell membranes and plays a role as a messenger in regulating metabolism in complex with calmodulin and other proteins [White and Broadley 2003, Starck 2007]. The distribution of Ca in plant is influenced by factors such as humidity, root pressure and phytohormone activity (Kirkby and Pilbeam 1984)

In own study, drip irrigation and cultivars did not significantly affect the Ca content of asparagus green spears (tab. 29) in the study years. However, the Ca content of spears in drip irrigated plots was slightly higher compared to non-irrigated plots.

Table 29. The content of Ca [g·kg-1 dm] of asparagus green spears cultivars in years of research (own preparation)

Irrigation	Cultivar	Studied year 2020	2021	2022	2023	Mean
0	Cumulus	2.62	2.24	3.01	2.58	**2.6**
	Bacchus	3.03	3.41	2.80	2.94	**3.05**
	Gyjnlim	2.54	2.67	2.86	2.72	**2.70**
	Mondeo	2.76	2.79	2.99	2.83	**2.84**
	Mean	**2,74**	**2.78**	**2.92**	**2.76**	**2.80**
D	Cumulus	2.79	2.25	2.91	2.65	**2.65**
	Bacchus	3.12	2.95	3.01	3.02	**3.03**
	Gyjnlim	2.98	2.79	3.14	2.81	**2,93**
	Mondeo	3.20	2.51	3.41	3.02	**3.04**
	Mean	**3.02**	**2.63**	**3.12**	**2.88**	**2.91**
LSD $_{0.05}$						
Irrigation (I)		ns	ns	ns	ns	ns

Cultivar (II)	ns	ns	ns	ns	ns
Interaction (IxII)	ns	ns	ns	ns	ns
Interaction (IIxI)	ns	ns	ns	ns	ns

5.10. SUMMER STALKS HEALTHINESS

Various asparagus cultivars were characterized by different susceptibility on infestation by *Puccinia asparagi*, *Stemphylium vesicarium*, *Botriytis cinerea* and *Fusarium.* The most severe symptoms of rust and *Stemphylium* leaf spot were observed on the 'Gyjnlim' and 'Mondeo' cultivars on both irrigation variants (tab. 30 and 31). Cultivars 'Cumulus ' and 'Bacchus' were significantly lower infested. The infestation index in consecutive years reached up to 19.4% and 30,1% for 'Cumulus' and 22.1% and 31.4% for 'Bacchus' for rust and *Stemphylium* leaf spot respectively. 'Gyjnlim' was the most susceptible, but the infestation index not exceed 24.7% for the rust, and 33,4% for *Stemphylium* leaf spot. Investigated cultivars may be characterized by mean susceptibility to examined pathogens. High variability in cultivars resistance to diseases were shown by different authors [Benson 2002; Broadhurst 1996; Knaflewski 1996].

Irrigation variants influenced the pathogens development. The rust development was stimulated, but *Stemphylium* leaf spot was restricted by investigated irrigation variants.

Significantly higher infection of plants with *P. asparagi* was observed on irrigated plots. The opposite tendency occurred for *Stemphylium* leaf spot. Generally the irrigation significantly decreased the infestation with that patogen in case of all cultivars tested.

In the successive years of the study, after planting of asparagus rootstock, intensity of occurrence of diseases was considerably higher. Relatively high infection with rust was observed especially in 2019 which was characterized by average amounts of rainfall and moderate temperatures during the vegetation period (tables 5). The infestation of *Stemphylium* were observed in 2020 which was characterized by highest rainfall and lowest temperaturs (tab. 31). The similar tendences were found in investigation of Panka et al. (2015) and Panka and Rolbiecki (2008) in experiments with the use of drip irrigation in differnt cultivars.

Infection of plants with *B. cinerea* and *Fusarium* spp. was on a similar level as rust and *Stemphylium* leaf spot (tab. 32 and 33). In the first case an infection index of plants did not exceed 15,7%, but in the second case the maximum percentage of plants with disease symptoms was 22,1%. The most susceptible to gray mould was cultivar 'Mondeo' and the most tolerant was cultivar 'Gyjnlim'. Very similar oservations were found at the experiments curried out with irrigated Dutch cultivars by Panka and Rolbiecki [2008]. Influence of irrigation on gray mould occurrence was not observed. A significant higher number of plants with *Fusarium* rot symptoms was found in non-irrigated plots. According to Nigh

[1990] stress factors such as dry periods can favor the development *of Fusarium* rot on plants. Elmer and LaMondia [1998] obtained similar results. Knaflewski [1996] found 'Jersey King' as the most tolerant cultivar to asparagus rust and gray mould and 'UC 157' the most susceptible.

Differentiation of susceptibility of cultivars for infection with pathogens was very high. Cultivars grown under other climatic conditions than their mother region and differentiation of pathogenicity within the pathogen species, cause that such cultivars can be infected in different degree [Benson 2002].

Table 30. Occurrence of asparagus rust (infection index in %) on asparagus cultivars, combined with the effect of irrigation during the irrigation seasons

Irrigation	Cultivar	Studied year				Mean
		2019	2020	2021	2022	
O	Cumulus	16.2	4.28	2.45	3.55	6.62
	Bacchus	17.1	5.25	1.56	3.23	6.78
	Gyjnlim	22.6	5.92	1.76	4.28	8.64
	Mondeo	18.1	7.32	1.67	6.78	8.46
	Mean	**18.5**	**5.69**	**1.86**	**4.46**	**7.62**
D	Cumulus	19.4	6.22	2.78	4.87	8.31
	Bacchus	22.1	6.53	2.87	4.05	8.88
	Gyjnlim	24.7	8.11	2.76	4.92	10.12
	Mondeo	21.2	8.41	3.02	8.54	10.29
	Mean	**21.85**	**7.31**	**2.85**	**5.59**	**9.40**
LSD $_{0.05}$						
Irrigation (I)		**0.559**	**n.s.**	**0.025**	**0.027**	**1.723**
Cultivar (II)		**0.219**	**n.s.**	**0.024**	**0.023**	**2,181**
Interaction (IxII)		**0.309**	**n.s.**	**0.034**	**0.030**	**n.s.**
Interaction (IIxI)		**0.571**	**n.s.**	**0.031**	**0.031**	**n.s.**

Table 31. Occurrence of *Stemphylium* leaf spot (infection index in %) on asparagus cultivars, combined with the effect of irrigation during the irrigation seasons

Irrigation	Cultivar	Studied year				Mean
		2019	2020	2021	2022	
O	Cumulus	1.63	30.1	13.70	1.21	11.66
	Bacchus	1.52	31.4	12.90	0.57	11.60
	Gyjnlim	3.11	33.4	14.32	0.67	12.87
	Mondeo	2.10	32.7	13.76	0.46	12.25
	Mean	**2.09**	**31.84**	**13.67**	**0.72**	**12.1**
D	Cumulus	1.69	24.9	11.50	0.55	9.66
	Bacchus	1.71	28.2	10.3	0.62	10.2
	Gyjnlim	2.87	32.1	12.1	0.32	11.84
	Mondeo	2.02	29.8	13.02	0.44	11.32
	Mean	**2.07**	**28.80**	**11.73**	**0.48**	**10.76**
LSD $_{0.05}$						
Irrigation (I)		**0.007**	**0.252**	**0.360**	**0.019**	**0.912**
Cultivar (II)		**0.034**	**0.473**	**0.226**	**0.006**	**1.675**
Interaction (IxII)		**0.047**	**0.669**	**0.320**	**0.009**	**ns**
Interaction (IIxI)		**0.031**	**0.480**	**0.392**	**0.019**	**ns**

Table 32. Occurrence of gray mould on asparagus (Infection index in %) for different cultivars, combined with the effect of irrigation during the irrigation seasons

Irrigation	Cultivar	Studied year 2019	2020	2021	2022	Mean
O	Cumulus	9.7	12.2	6.7	7.5	9.0
	Bacchus	6.8	7.9	10.7	8.4	8.4
	Gyjnlim	5.7	6.4	7.1	7.4	6.6
	Mondeo	12.0	11.3	15.7	11.6	12.6
	Mean	**8.55**	**9.4**	**10.05**	**8.72**	**9.1**
D	Cumulus	10.0	12.5	6.9	7.9	9.3
	Bacchus	8.3	8.1	12.1	9.2	9.4
	Gyjnlim	7.2	6.8	7.9	8.7	7.6
	Mondeo	9.8	11.7	13.6	10.2	11.0
	Mean	**8.82**	**9.7**	**10.13**	**9.0**	**9.3**
LSD 0.05						
Irrigation (I)		0.062	0.108	**0.036**	**n.s.**	ns
Cultivar (II)		0.061	0.105	0.035	**n.s.**	2.837
Interaction (IxII)		0.086	ns	0.049	**n.s.**	ns
Interaction (IIxI)		0.078	ns	0.045	**n.s.**	ns

Table 33. Occurrence of asparagus plants with symptoms of *Fusarium* rot on stems, for different cultivars, combined with the effect of irrigation during the irrigation seasons

Irrigation	Cultivar	Studied year 2019	2020	2021	2022	Mean
O	Cumulus	22.1	15.3	12.2	13.4	15.7
	Bacchus	19.7	13.9	15.1	14.4	15.8
	Gyjnlim	6.5	8.6	10.2	9.9	8.8
	Mondeo	7.3	9.6	11.4	10.4	9.6
	Mean	**13.9**	**11.8**	**12.2**	**12.0**	**12.5**
D	Cumulus	15.2	12.2	11.4	12.6	12.8
	Bacchus	16.5	12.1	14.7	13.1	14.1
	Gyjnlim	4.1	6.7	8.9	8.3	7.0
	Mondeo	6.1	7.4	10.3	9.7	8.3
	Mean	**10,4**	**9.6**	**11.3**	**10.9**	**10.5**
LSD 0.05						
Irrigation (I)		0.037	ns	**0.284**	0.435	1.857
Cultivar (II)		0.035	0.561	0.099	0.637	3.722
Interaction (IxII)		0.050	ns	0.140	ns	ns
Interaction (IIxI)		0.045	ns	0.254	ns	ns

6. CONCLUSIONS

I. Water requirements associated with field water consumption (S) of asparagus in organic cultivation grown in light soil under optimal soil moisture conditions during the irrigation season were variable and dependent on rainfall patterns in subsequent growing seasons.

II. Field water consumption under subsurface drip irrigation (S_D) averaged 168 mm in the non-yielding plantation and 241 mm in the yielding plantation.

III. Daily water consumption increased with the growth of asparagus summer stalks during the irrigation season from June to August.

IV. The average value of reference evapotranspiration (ET_o) for the asparagus irrigation period calculated using the using the Hargreaves model modified by Droogers and Allen amounted to 338 mm.

V. The values of plant coefficients (k_c) for the Hargreaves model modified by Droogers and Allen (k_c^{HDA}) were as follows: in June – 0.33; July – 0.35; August – 0.52. The plant coefficients (k_c) in the irrigation period of the yielding plantation for the Hargreaves model modified by Droogers and Allen (k_c^{HDA}), were: in June – 0.33; July – 0.76; August – 0.82.

VI. Crop evapotranspiration of asparagus, calculated using the Hargreaves model modified by Droogers and Allen (ET_{cD}^{HDA}), averaged 83 mm on a non-yielding plantation and 240 mm on a yielding plantation.

VII. Postharvest drip irrigation applied during the growing season significantly affected green spear yield, increasing it from 3.92 $t \cdot ha^{-1}$ to 5.34 $t \cdot ha^{-1}$ over the four-year study period. The highest marketable yield was recorded in the Cumulus cultivar (6.98 $t \cdot ha^{-1}$), indicating a strong positive response.

VIII. Drip irrigation also significantly influenced spear weight by increasing the mean spear weight from 38.23 g in 2020 to 44.19 g in 2023. The Mondeo cultivar showed the highest average spear weight (42.69 g) under subsurface drip irrigation.

IX. The number of spears per plant was significantly enhanced, rising from 9.97 to 10.79. The Cumulus cultivar demonstrated the most substantial increase, averaging 11.97 spears per plant.

X. Overall, these findings suggest that postharvest drip irrigation is an effective agronomic practice for improving both yield and spear quality in *Asparagus officinalis*, particularly in responsive cultivars such as Cumulus and Mondeo.

XI. Drip irrigation significantly affected on the asparagus summer stalks features such: height, number, diameter and weight of the stalks. On irrigated plots summer stalks were taller (218 cm) compared to non-irrigated ones (186 cm), with the highest average height observed in ‘Cumulus’, ‘Bacchus’, and ‘Mondeo’ (221 cm). Stalk diameter increased from 15 mm to 19 mm under irrigation, with ‘Cumulus’ and ‘Gijnlim’ reaching 20 mm. The number of summer stalks per plant increased from 3 to 4 on average. Additionally, drip irrigation enhanced stalk weight, with ‘Gijnlim’ recording the highest yield (4.02 kg).

XII. The biochemical composition of asparagus spears was considerably influenced by the application of drip irrigation during the growing season. While chlorophyll content significantly increased under irrigation, anthocyanin, dry matter, and mineral contents were generally higher in non-irrigated plots. Carotenoid accumulation was mainly dependent on cultivar and year, rather than irrigation. ‘Mondeo’ had the highest levels of chlorophyll and anthocyanin, whereas ‘Gijnlim’ was prominent for carotenoid and mineral content.

XIII. The most tolerant to *P. asparagi* and *S. vesicarium* were cultivars 'Gijnlym', 'Mondeo'. Significantly higher infection of plants with *P. asparagi* was observed on irrigated plots. The opposite tendency occurred for *Stemphylium* leaf spot. Generally the irrigation significantly decreased the infestation with that patogen in case of all cultivars tested. Differentiation of susceptibility of particular cultivars for infection with pathogens was very high. In general, irrigation limited occurrence of *Stemphylium* leaf spot and *Fusarium* spp. on asparagus. Obtained results show the importance of irrigation as a factor which can both increase productivity of asparagus, as well as improve plant health.

XIV. The use of modern subsurface drip irrigation technology increases the production capacity of very light soil by ensuring optimal soil moisture conditions, allowing for high and good quality yields of asparagus in organic cultivation.

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8. ABSTRACT

Influence of subsurface drip irrigation on the growth and yielding of asparagus in organic system on the light soil

MSc Hicran sadan-Ozdemir

Key words: organic cultivation, asparagus, water needs, yield, spears quality

This study aimed to evaluate the effect of subsurface drip irrigation on the growth, yield, and spear quality of *Asparagus officinalis* cultivated under organic conditions on light, sandy soils. The water needs of asparagus were also estimated according to field water consumption and climatic model. The experiment was conducted between 2019 and 2023 on an ecological farm in northern Poland. Two factors were examined in the experiment and were as follows: I factor – subsurface drip irrigation: O – without irrigation (control), D – with subsurface drip irrigation, and II factor – cultivars: 'Cumulus', 'Bacchus', 'Gijnliym', 'Mondeo'. Key growth parameters of summer stalks (height, diameter, number, and weight) were assessed, along with total and marketable yields. Additionally, spear quality was analyzed.

Field water consumption under subsurface drip irrigation (SD) averaged 168 mm in the non-yielding plantation and 241 mm in the yielding plantation. Daily water consumption increased with the growth of asparagus summer stalks during the irrigation season from June to August. The values of plant coefficients (k_c) for the Hargreaves model modified by Droogers and Allen (k_c^{HDA}) were as follows: in June – 0.33; July – 0.35; August – 0.52. The plant coefficients (kc) in the irrigation period of the yielding plantation for the Hargreaves model modified by Droogers and Allen (k_c^{HDA}), were: in June – 0.33; July – 0.76; August – 0.82.

Postharvest drip irrigation applied during the growing season significantly affected green spear yield, increasing it from 3.92 $t \cdot ha^{-1}$ to 5.34 $t \cdot ha^{-1}$ over the four-year study period. The highest marketable yield was recorded in the Cumulus cultivar (6.98 $t \cdot ha^{-1}$), indicating a strong positive response. Drip irrigation also significantly influenced spear weight by increasing the mean spear weight from 38.23 g in 2020 to 44.19 g in

2023. The Mondeo cultivar showed the highest average spear weight (42.69 g) under subsurface drip irrigation. The number of spears per plant was significantly enhanced, rising from 9.97 to 10.79. The Cumulus cultivar demonstrated the most substantial increase, averaging 11.97 spears per plant.

Drip irrigation significantly affected on the asparagus summer stalks features such: height, number, diameter and weight of the stalks. On irrigated plots summer stalks were taller (218 cm) compared to non-irrigated ones (186 cm), with the highest average height observed in 'Cumulus', 'Bacchus', and 'Mondeo' (221 cm). Stalk diameter increased from 15 mm to 19 mm under irrigation, with 'Cumulus' and 'Gijnlim' reaching 20 mm. The number of summer stalks per plant increased from 3 to 4 on average. Additionally, drip irrigation enhanced stalk weight, with 'Gijnlim' recording the highest yield (4.02 kg).

The biochemical composition of asparagus spears was considerably influenced by the application of drip irrigation during the growing season. The use of modern subsurface drip irrigation technology increases the production capacity of very light soil by ensuring optimal soil moisture conditions, allowing for high and good quality yields of asparagus in organic cultivation.

9. STRESZCZENIE

Wpływ podpowierzchniowego nawadniania kroplowego na wzrost i plonowanie szparagów w systemie ekologicznym na glebie lekkiej

Mgr inż. Hicran Sadan-Ozdemir

Słowa kluczowe: uprawa ekologiczna, szparag, potrzeby wodne, plon, jakośc wypustek

Celem niniejszej pracy była ocena wpływu nawadniania kroplowego na wzrost, plonowanie i jakość wypustek szparaga uprawianego w warunkach ekologicznych na glebach lekkich, piaszczystych. Zapotrzebowanie na wodę szparagów oszacowano na podstawie polowego zużycia wody i modelu klimatycznego. Doświadczenie przeprowadzono w latach 2019-2023 w gospodarstwie ekologicznym w północnej Polsce. W doświadczeniu badano dwa czynniki: czynnik I – nawadnianie kroplowe: O – bez nawadniania (kontrola), D – z nawadnianiem kroplowym oraz czynnik II – odmiany: 'Cumulus', 'Bacchus', 'Gijnliym', 'Mondeo'. Oceniono kluczowe parametry wzrostu pędów asymilacyjnych (wysokość, średnica, liczba i masa), a także plon całkowity i handlowy. Dodatkowo przeanalizowano jakość wypustek. Średnie polowe zużycie wody w systemie nawadniania kroplowego (SD) wynosiło 168 mm na plantacji nieplonującej i 241 mm na plantacji plonującej. Dzienne zużycie wody wzrastało wraz ze wzrostem pędów asymilacyjnych szparaga w sezonie nawadnieniowym od czerwca do sierpnia. Wartości współczynników roślinnych (k_c) dla modelu Hargreavesa w modyfikacji Droogersa i Allena (k_c^{HDA}) były następujące: w czerwcu – 0,33; lipcu – 0,35; sierpniu – 0,52. Współczynniki roślinne (k_c) w okresie nawadniania plantacji plonującej wyniosły: w czerwcu – 0,33; lipcu – 0,76; sierpniu – 0,82. Nawadnianie kroplowe po zbiorach, stosowane w okresie wegetacyjnym, znacząco wpłynęło na plon zielonych wypustek, zwiększając go z 3,92 $t \cdot ha^{-1}$ do 5,34 $t \cdot ha^{-1}$ w czteroletnim okresie badań. Najwyższy plon handlowy odnotowano w przypadku odmiany 'Cumulus' (6,98 $t \cdot ha^{-1}$), co wskazuje na silną pozytywną reakcję. Nawadnianie kroplowe również znacząco wpłynęło na masę wypustek, zwiększając średnią masę wypustek z 38,23 g w 2020 r. do 44,19 g w 2023 r. Odmiana 'Mondeo' charakteryzowała się najwyższą średnią masą wypustek (42,69 g) w warunkach podpowierzchniowego nawadniania kroplowego. Liczba wypustek na roślinę uległa znacznemu zwiększeniu, wzrastając z 9,97 do 10,79. Odmiana 'Cumulus' wykazała największy wzrost, osiągając średnio 11,97 wypustek na roślinę.

Nawadnianie kroplowe istotnie wpłynęło na cechy pędów asymilacyjnych szparagów, takie jak wysokość, liczba, średnica i masa pędów. Na poletkach nawadnianych pędy były wyższe (218 cm) w porównaniu do nienawadnianych (186 cm), przy czym najwyższą średnią wysokość zaobserwowano u odmian ‘Cumulus’, ‘Bacchus’ i ‘Mondeo’ (221 cm). Średnica pędów wzrosła z 15 mm do 19 mm pod wpływem nawadniania, przy czym ‘Cumulus’ i ‘Gijnlim’ osiągnęły 20 mm. Liczba pędów asymilacyjnych na roślinę wzrosła średnio z 3 do 4. Ponadto nawadnianie kroplowe zwiększyło masę pedów. Najwyższą masą charakteryzowała się odmiana ‘Gijnlim’(4,02 kg).
Nawadnianie kroplowe w okresie wegetacji wpłynęło również istotnie na skład biochemiczny wypustek szparagów.

Zastosowanie nowoczesnej technologii podpowierzchniowego nawadniania kroplowego zwiększa efektywność produkcji na glebach bardzo lekkich, zapewniając optymalne warunki wilgotnościowe, co pozwalało na uzyskanie wysokich i dobrej jakości plonów szparagów w uprawie ekologicznej.