The Role of Beneficial Microorganisms in Onion (*Allium cepa*) Cultivation

- A Scientific Review and an Interview Study of Farmers' Awareness in Sweden

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Abstract

Onion (*Allium cepa*) is a globally important horticultural crop. Its cultivation faces increasing challenges from climate change, soil degradation, and rising disease pressure. Modern agriculture must address these issues while advancing towards sustainable production in line with the United Nations Sustainable Development Goals. Plant-associated beneficial microorganisms, including beneficial bacteria and fungi, have emerged as promising tools for enhancing crop growth, nutrient uptake, disease resistance, and stress tolerance. This study presents a comprehensive scientific review of the current knowledge on the role of beneficial microorganisms in onion cultivation. In addition, an interview-based survey was conducted with Swedish onion farmers to assess their awareness, perceptions, and adoption of microbiome-based agricultural practices. The findings reveal that while scientific evidence supports the benefits of microbiome management in onions, practical application in Sweden remains limited by knowledge gaps and resource constraints. The study highlights strengthening farmer education and integrating microbiome strategies can support more sustainable and resilient onion production, aligning with the United Nations Sustainable Development Goals.

Keywords: arbuscular mycorrhizal fungi, beneficial microorganisms, onion (*Allium cepa*), phosphorus-solubilizing bacteria, plant growth-promoting rhizobacteria, sustainable agriculture, Sweden

Table of contents

List of figures

Abbreviations

AMF	Arbuscular Mycorrhizal Fungi
FBR	Fusarium Basal Rot
K	Potassium
N	Nitrogen
NaCl	Sodium chloride
P	Phosphorus
PGPB	Plant Growth-Promoting Bacteria
PGPR	Plant Growth-Promoting Rhizobacteria
PSB	Phosphorus-Solubilizing Bacteria
S	Sulphur
SDG	Sustainable Development Goal
AMF	Arbuscular Mycorrhizal Fungi

1. Introduction

1.1 Onion Production: Global and Sweden

Onion (*Allium cepa*) is an economically important crop which belongs to the family Alliaceae and is a relative to garlic (*Allium sativum*), leeks (*Allium ampeloprasum*), chives (*Allium schoenoprasum*) and shallot (*Allium ascalonicum*) (Ochar and Kim 2023). Onion is one of the most produced vegetables globally, second only tomato. In 2023, approximately 111.27 million metric tons of dry onions were produced worldwide (Statista 2025). India, China and Egypt are the top onion producers in the world (World Population Review 2025) and the Netherlands, Spain and France are the major onion producing countries in Europe (Eurostat 2024).

In Sweden, onion cultivation plays an essential role in horticulture, contributing to both local consumption and export markets. Sweden's onion production has shown a steady upward trend over the years. The last five years, since 2017, onion production has increased annually by approximately 1.9%, with production reaching 69.15 million kilograms in 2022, compared to 30 million kilograms in 2008, reflecting significant growth over the past decade (TRIDGE n.d.; ReportLinker 2022). The area under cultivation for onions has also fluctuated, reaching a peak of 1.58 thousand hectares in 2022 before declining slightly to 1.49 thousand hectares by 2023 (Trading Economics 2025).

1.2 The Role of beneficial Microorganisms in Plants

Beneficial microorganisms play a crucial role in horticultural crop production by influencing plant growth, nutrient uptake, disease resistance, and overall plant health. Particularly those microorganisms that are associated with plant roots (rhizosphere), leaves (phyllosphere), and internal plant tissues (endosphere), play a significant role in plants (Compant et al. 2019). Plant Growth-Promoting Rhizobacteria (PGPR) help the plant to grow well in their presence by various mechanisms. The direct mechanism may include fixation of atmospheric nitrogen, synthesis of various phytohormones and enzymes, and solubilization of minerals in the soil, while the indirect mechanism includes inhibiting phytopathogens (Sayyed et al. 2019). And also, Arbuscular Mycorrhizal Fungi (AMF), the fungi which make a symbiotic association with plant roots, are also beneficial for plant growth and nutrient uptake (Shub et al. 2014).

1.3 Research Gap

Modern agriculture faces the dual challenge of increasing food production to meet the demands of a growing global population while maintaining environmental sustainability. Unpredictable climate events such as droughts, heatwaves, and floods, along with pressure from pests, diseases, and weeds, continue to threaten crop health and productivity. These combined stresses have significant consequences for both human food security and livestock feed availability. One promising approach to addressing these challenges is through the use of plant microbiomes (Xue et al. 2024). These beneficial microorganisms enhance plant resilience by improving nutrient uptake efficiency, stimulating natural disease resistance mechanisms, and increasing tolerance to abiotic stresses such as drought and salinity. This allows crops to perform better under adverse environmental conditions while reducing reliance on chemical inputs (Compant 2019; Parks 2022). The United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation) SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), emphasize the urgent need for resilient, resource-efficient, and environmentally sound agricultural practices (THE 17 GOALS | Sustainable Development, n.d.).

While microbiome research has gained attention in staple crops such as wheat, rice, and maize (Michl et al. 2023), studies on microbiome interactions in onion cultivation remain limited. Additionally, the level of awareness among Swedish farmers regarding the potential of microbiomes in sustainable farming is unclear. To raise awareness, farmers need knowledge not only about the general benefits of beneficial microorganisms. For examples improved nutrient cycling, stress tolerance, and disease suppression. And also, about specific microbial groups (e.g., PGPR, AMF, PSB) and how to apply them effectively under local conditions. Bridging this gap requires practical, targeted education that combines scientific findings with clear guidance on microbial selection, application methods, and compatibility with existing farming systems.

Understanding the current state of microbiome research and assessing farmers' perceptions can help bridge the gap between scientific advancements and practical implementation.

1.4 Aim, Research Questions and Hypothesis

Aim:

This study aims to,

I. conduct a comprehensive scientific review of beneficial microorganisms associated with onion cultivation, focusing on their roles in plant growth, disease resistance, and stress tolerance,

II. investigate the level of awareness and perception of Swedish onion farmers regarding beneficial microorganisms-based agricultural practices.

Research Questions:

This study focuses on addressing the following research questions,

I. What type of beneficial microorganisms are associated with onion production?

II. How could beneficial microorganisms help onions to improve nutrient uptake, disease resistance, and stress tolerance?

III. How much do Swedish onion farmers know about beneficial microorganisms and their benefits?

IV. What are potential sustainable beneficial microorganisms -based solutions to onion farming?

Hypotheses:

This study is based on the following hypotheses,

I. Beneficial microorganisms significantly contribute to plant growth, disease resistance, and stress tolerance in onion cultivation.

II. Swedish onion farmers have limited awareness and adoption of beneficial microorganisms -based agricultural practices.

By addressing these objectives and testing these hypotheses, this study aims to explore both the scientific potential of beneficial microorganisms in enhancing onion cultivation and the current level of knowledge about beneficial microorganisms among Swedish onion farmers. Understanding both aspects is essential for bridging the gap between research and practical application, and for guiding future efforts toward more sustainable and resilient onion production

2. Background

2.1 Onion

Onion is a popular vegetable grown and used all over the world. It is mainly grown for its underground bulb, which is used in cooking. Onions have a distinctive flavour and pungency, which come from natural sulfur compounds present in the scales of bulbs. These compounds are released when the onion tissues are broken. People eat onions raw in salads or cook them in many ways, like in curries, fried, boiled, baked, or in soups and pickles (Lawande 2012; Kumar et al. 2019).

Onions are not only an important vegetable crop but also a valuable source of nutrition due to their rich biochemical composition. They contain beneficial bioactive compounds such as flavonoids, phenolic compounds, organosulfur compounds, and polysaccharides, which contribute to various health benefits (Goldman 2011; Ko et al. 2015). Examples of health benefits are including anti-cancer properties, antiplatelet activity, antithrombotic activity and activity against asthma (Griffiths et al. 2002). Because onions are widely consumed around the world, even small improvements in the levels of these health-promoting substances could have a meaningful impact on global public health (Mogren 2006).

Successful onion production depends on specific pedoclimatic conditions, including optimal temperatures of 15–20°C for vegetative growth and 20–27°C for bulb development. Additionally, onions require a soil pH between 6.0 and 7.0 and a water supply of approximately 350–550 mm, with regular irrigation necessary to maintain high soil moisture for optimal yields (Al-Jamal et al. 2000; Sansan et al. 2024).

2.1.1 Origin and Distribution

Onion is one of the oldest cultivated vegetables in the world. The precise origin of the onion remains uncertain. Most researchers and historians believe it was first domesticated in Central Asia, with other evidence pointing to regions in Iran and West Pakistan as possible centers of origin. Onions have been cultivated for at least 5,000 or more years, in ancient Egypt, India, and China, making them one of the earliest domesticated crops. (Mehta 2017; National Onion Association 2024).

From their center of origin, onions spread to Europe, Africa, and the rest of Asia through trade routes and human migration. Today, onions are cultivated in more than 140 countries across all continents. The wide distribution of onions is due to their ability to grow in a range of climates, from temperate to tropical regions (Ochar 2023; Mehta 2017).

2.1.2 Taxonomy and Botany

The classification of onions has been discussed and changed many times. Onions were previously placed in the Liliaceae family, but considering the inflorescence structure, later it was moved to the Amaryllidaceae family. With the help of molecular biology, onions were enabled to be classified under the Alliaceae family (Sansan et al. 2024).

Scientific Classification:

Class	: Monocotyledonae
Order	: Asparagales
Family	: Alliaceae
Tribe	: Allieae
Genus	: *Allium*
Species	: *Allium cepa*

(Sansan et al. 2024).

Botanically, the onion is a bulbous plant with a short stem called a plateau. It has cylindrical, hollow leaves growing from the upper part and many adventitious roots growing from the lower part. The leaves are arranged alternately in two opposite rows. Onion roots are numerous, whitish, shallow, and slightly branched, usually reaching a depth of about 20–25 cm into the soil. Because of this shallow root system, onions cannot absorb water from deep soil layers, making them more sensitive to drought. Onion flowers have trimeric symmetry, meaning they have three sepals and three petals. Each flower has six stamens and a three-lobed ovary, with each part containing two large ovules. Pollen is released before the stigma becomes receptive, which encourages cross-pollination between plants. Each flower cluster can produce between 100 and 1,500 seeds. The onion bulb is made up of tunics with cataphylls or concentric, fleshy, and transparent scales. Depending on the variety, the bulb color can be yellow, red, white, or a mix of these colours (Sansan et al. 2024).

2.1.3 Onion Growing Areas in Sweden

Onion cultivation in Sweden is geographically concentrated in the southern regions and the Baltic Island of Öland, where climatic and soil conditions are most favorable. The southern province of Skåne (Scania) and the island of Öland are the primary production hubs, with Öland having a centuries-old tradition of onion farming (FreshPlaza, 2025).

2.1.4 Challenges in Onion Cultivation

Onion cultivation faces a range of interconnected challenges that impact productivity and sustainability. Climate change is a major factor, with increased frequency of drought, unseasonal rainfall, temperature fluctuations, and extreme weather events leading to reduced yields and greater vulnerability to diseases and pests. These climatic stresses not only directly affect onion growth and bulb development, but also create favourable conditions for the emergence and spread of diseases such as damping-off (*Pythium spp., Fusarium spp*.), purple blotch (*Alternaria porri*), onion smut (*Urocystis cepulae*), and anthracnose (*Colletotrichum spp*.) requiring more frequent and costly use of chemical fertilizers and pesticides (Agale & Thaware 2020).

Intensive use of mineral fertilizers to boost yields has led to deterioration of soil properties, including reduced organic carbon content and imbalanced mineral availability. Degraded soil health can lower productivity and make onions more susceptible to stress and disease. Practices such as crop rotation are often neglected, further depleting soil nutrients and microbial diversity. However, integrating biochar, organic amendments, or plant growth-promoting microorganisms can help restore soil fertility, improve nutrient uptake, and enhance yield and bulb quality (Aneseyee and Wolde 2021; Arunachalam et al. 2024). Biochar improves soil structure, water retention, and cation exchange capacity, thereby supporting microbial activity and nutrient availability (Hossain et al. 2020). Organic amendments such as compost increase organic matter content and stimulate microbial diversity, which in turn promotes nutrient mineralization (Ros et al. 2006). Plant growth-promoting microorganisms enhance nutrient solubilization (e.g., phosphorus), produce phytohormones, and improve root development factors that collectively lead to better plant vigor, higher yields, and improved bulb size and quality (Aneseyee and Wolde 2021).

In addition to environmental and agronomic challenges, postharvest losses such as sprouting significantly affect onion storability and marketability. Recent research has shown that sugar content and dry matter are key factors predicting the likelihood of sprouting in yellow bulb onions, regardless of treatment with maleic hydrazide. Specifically, higher concentrations of sugars like fructose and glucose, as well as overall dry matter content, are strongly associated with increased sprouting during storage (Kleman et al. 2024).

2.2 Beneficial Microorganisms in Agriculture

Beneficial microorganisms are naturally occurring or deliberately introduced microbes that promote plant health and growth through a variety of mechanisms. These include plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF) and phosphorus-solubilizing bacteria (PSB). PGPR fix atmospheric nitrogen, solubilize phosphate, and produce phytohormones like auxins and gibberellins (Sayyed et al. 2019). AMF form symbiotic associations with plant roots to improve water and nutrient uptake, particularly phosphorus (Shub et al. 2014). PSB convert insoluble forms of phosphorus into bioavailable forms for plant use. Other beneficial microbes include endophytes that reside within plant tissues and enhance resistance to pathogens and abiotic stresses (Arunachalam et al. 2024). By improving nutrient efficiency, enhancing tolerance to drought and salinity, and suppressing soil-borne diseases, beneficial microorganisms contribute significantly to sustainable agricultural systems. Their integration into crop management practices offers an eco-friendly alternative to synthetic fertilizers and pesticides.

2.3 Microbiomes

A microbiome can be best described as a collective polymicrobial community, or 'microbiota', along with its associated activities and the genetic and physio-chemical components within a defined spatial and temporal habitat (Parks 2022). This community includes diverse microorganisms such as bacteria, archaea, algae, protozoa, fungi, and viruses. The inclusion of viruses is debated since they are not technically living organisms. The microbiome concept not only encompasses the microorganisms themselves but also their "theatre of activity," which involves their structural elements, metabolites, mobile genetic elements (like phages and plasmids), and interactions with the surrounding environment (Figure 1:) (Berg et al. 2020). Microbiomes are found everywhere: in soil, water, air, and within living organisms such as plants and animals (Parks 2022).

A plant microbiome refers specifically to the diverse community of microorganisms that live on and inside plants. These microbes can inhabit different parts of the plant, such as the roots (rhizosphere), the above-ground surfaces like leaves and stems (phyllosphere), and even the internal tissues (endosphere). The plant microbiome acts as a microbial ecosystem, influencing plant health, growth, and resilience by helping plants absorb nutrients, resist diseases, and tolerate environmental stresses. The composition and function of plant microbiomes are shaped by factors like plant species, environment, and agricultural practices (Compant 2019; Parks 2022).

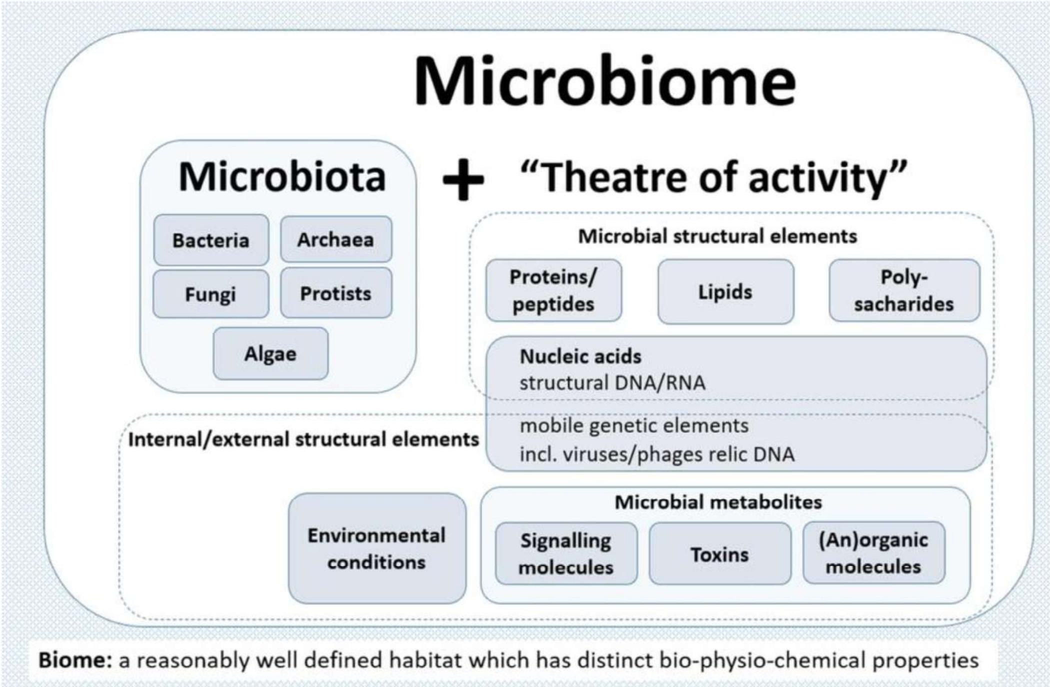

Figure 1: Composition of the term microbiome containing both the microbiota (community of microorganisms) and their "theatre of activity" (structural elements, metabolites/signal molecules, and the surrounding environmental conditions). (Berg et al. 2020) https://microbiomejournal.biomedcentral.com/articles/10.1186/s40168-020-00875-0 [2025-05-01]([CC-BY-SA-4.0](CC-BY-SA-4.0))

2.3.1 Rhizosphere Microbiomes

The rhizosphere is the narrow zone of soil directly influenced by plant roots and is considered a hotspot for plant-microbe interactions (Wu et al. 2023). This environment harbors a diverse community of microorganisms, including bacteria, fungi, archaea, and protists, which interact in complex networks (Li et al. 2021). Plants actively shape the composition and activity of their rhizosphere microbiome through the release of root exudates-compounds such as sugars, amino acids, and organic acids-which serve as nutrients and signalling molecules for microbes (Pantigoso et al. 2022; Wu et al. 2023). Beneficial rhizosphere microbes promote plant growth by increasing nutrient availability, producing plant hormones, and enhancing tolerance to biotic and abiotic stresses (Li et al. 2021). They also protect plants against pathogens through mechanisms such as antagonism, competition for resources, and enhancing microbial diversity. Mycorrhizal fungi, a key group in the rhizosphere, facilitate nutrient uptake and provide resistance to stress and pathogens (Li et al. 2021; Pantigoso et al. 2022). Overall, the rhizosphere microbiome plays a central role in nutrient cycling, organic matter decomposition, and plant health (Wu et al. 2023).

2.3.2 Phyllosphere Microbiomes

The phyllosphere refers to the above-ground surfaces of plants, primarily the leaves, which are colonized by a diverse array of microorganisms, including bacteria, fungi, and viruses. Although the diversity of phyllosphere microbes is generally lower than that of the rhizosphere, these communities are ecologically significant and play vital roles in plant health and ecosystem function. The composition of the phyllosphere microbiome is influenced by leaf nutrient content, plant species, and environmental factors. Phyllosphere microbes contribute to plant health by cycling carbon and nitrogen, producing bioactive molecules that can induce plant defences, and providing protection against foliar pathogens. Their interactions with the plant are shaped by the availability of nutrients on the leaf surface and environmental conditions (Liu et al. 2023).

2.3.3 Endosphere Microbiomes

The endosphere encompasses the internal tissues of plants, including roots, stems, and leaves, which are colonized by endophytic microorganisms-bacteria and fungi that live at least part of their life cycle within plant tissues without causing harm (Compant et al. 2021; Babalola and Adedayo 2023). These endophytes can enter plant tissues from the rhizosphere or through vertical transmission via seeds (Babalola and Adedayo 2023). Endophytic microbes play crucial roles in promoting plant growth, enhancing nutrient acquisition, and improving plant health by exchanging metabolites with their host and modulating plant physiological responses. The diversity and composition of endosphere communities are influenced by plant species, organ type, growth stage, and environmental conditions. Endophytes can also contribute to stress tolerance and pathogen resistance, making them important for plant fitness and ecosystem functioning (Compant et al. 2021; Babalola and Adedayo 2023).

2.4 Plant Microbiome-Based Technologies

Microbiome-based technologies refer to the use and manipulation of plant-associated microbiome to enhance plant growth, health, and resilience in a sustainable manner. These technologies encompass microbial inoculants, biofertilizers, biopesticides, biostimulants, and methods such as microbiome engineering or in situ modulation. Their goal is to support crop production by leveraging beneficial plant-microbe interactions instead of relying exclusively on chemical inputs (Qiu et al. 2019; Zhang et al. 2021).

These technologies are often grouped into two broad approaches: introducing beneficial microorganisms (e.g., PGPR, AMF, or endophytes) and modifying environmental conditions to favor naturally occurring beneficial microbes. For example, microbial consortia designed to improve phosphorus uptake or nitrogen fixation are already being tested in cereals like wheat and rice. Similarly, microbiome engineering modifying the soil or plant environment to shape microbial communities has shown promise in enhancing resilience to drought and pathogen attack (Albright et al. 2022).

Microbiome-based technologies are important for sustainable agriculture because they can reduce dependency on synthetic fertilizers and pesticides, restore degraded soils, and increase productivity under changing climatic conditions.

2.5 Examples of Beneficial Microorganisms Applications in Agriculture

The application of beneficial microorganisms in the horticulture sector has shown remarkable benefits across a wide range of crops beyond onion. For example, in tomato (*Solanum lycopersicum*), inoculated with AMF significantly improves the growth and nutrient uptake of tomato seedlings, especially under salt stress, by enhancing water and nutrient absorption and helping plants cope with salinity (Balliu et al. 2015). While phosphorus fertilization boosts tomato growth, excessive phosphorus can reduce AMF colonization and its benefits. Therefore, balanced phosphorus management is important to maximize the positive effects of AMF on tomato health and productivity (Higo det al. 2020).

In strawberry, the use of PGPR like *Bacillus subtilis* and *Pseudomonas fluorescens* has led to enhanced root growth, increased fruit quality, and reduced incidence of diseases such as gray mold (Backer et al. 2018; Compant et al. 2019).

The study by Islam et al. (2016) investigated indigenous PGPR from cucumber rhizosphere can be used to enhance plant growth and provide effective biological control against major soil-borne diseases, offering a promising alternative to chemical treatments.

In wheat, the bacterium *Pseudomonas piscium* has been shown to reduce the virulence of *Fusarium graminearum* by interfering with its histone acetylation (Chen et al. 2018). Similarly, *Pantoea agglomerans* has been identified as a biocontrol agent against Fusarium head blight (Michl et al. 2023).

In rice, *Sphingomonas melonis*, a seed endophytic bacterium, conferred resistance to seedling blight caused by *Burkholderia plantarii* through the production of anthranilic acid (Matsumoto et al. 2021).

In maize, the application of *Trichoderma harzianum* and *Trichoderma asperellum* reduced stalk rot caused by *Fusarium spp.* and reshaped the rhizosphere microbiome (Saravanakumar et al. 2017; He et al. 2019). Moreover, *Paenibacillus triticisoli* inoculation in maize improved biomass and nitrogen use efficiency under low nitrogen conditions (Li et al. 2021).

3. Methodology

3.1 Research Design

This thesis consists of a mixed methods approach, integrating a comprehensive literature review and a farmer survey. This method helps explore both the scientific knowledge of microbiomes in onion cultivation and Swedish onion farmers' current awareness about microbiomes.

3.2 Literature Review

The literature review was conducted to gather scientific information related to plant-microbe interactions, onion microbiomes, and sustainable onion farming practices. Academic search engines such as Web of Science and Google Scholar were primarily used to find relevant articles, books, reports, and databases. The keywords used were onion, *Allium cepa*, microbiomes, plant-microbe interactions, plant growth promoting rhizobacteria, mycorrhiza, Europe, Sweden, taxonomy, origin, etc. The keywords were used individually or in combination with boolean operators such as "AND" or "OR" to refine and broaden the literature search results.

3.3 Farmer Survey

To assess Swedish farmers' awareness and perceptions regarding microbiomes in onion cultivation, a survey was designed and carried out using both digital and in-person methods. For farmers located at a distance, the survey was distributed via Google Forms with the help of onion grower advisor. For farmers within accessible regions, hardcopy surveys were administered through direct visit, enabling clarification of questions and potentially richer responses. This mixed approach helped increase the response rate and ensured a diverse range of participants.

The survey targeted onion growers in Sweden. The questionnaire consisted of ten structured questions. Topics covered general farming information, awareness and perceptions of microbiomes, practices and challenges in onion production. The survey was carried out from 2025-04-21 to 2025-05-01.

According to information provided by the advisor (field vegetables), there are approximately 50 onion farmers in Sweden (Hansson 2025). For this study, data were collected from 13 farmers.

Participation in the survey was voluntary, and respondents were informed about the purpose of the study and the confidentiality of their responses. Data were anonymized to protect participants' identities.

4. Results

4.1 Literature Review

4.1.1 Effects of Beneficial Microorganisms on Onion Plant Growth and Nutrients Uptake

Arbuscular Mycorrhizal Fungi (AMF):

Shuab et al. (2014) found that inoculating onion plants with AMF, particularly species from the *Glomus* genus, significantly improved various growth parameters compared to non-inoculated control plants. Inoculated onions showed higher plant height, root length, leaf number, chlorophyll content, fresh and dry biomass, and bulb diameter. These effects were most prominent between 40 and 80 days after planting. And also, microscopic observation confirmed that AMF colonization occurred only in the roots, not in the bulb or scale tissues. This confirms that the root system is the exclusive site for AMF interaction in onions. The enhanced growth in inoculated plants is mainly attributed to improved phosphorus uptake, as onion plants naturally have shallow and sparse roots with low efficiency in absorbing nutrients.

Phosphorus-Solubilizing Bacteria (PSB) and Endophytic Fungi:

Arunachalam et al. (2024) found that applying PSB and the endophytic fungus, *Serendipita indica,* in combination with recommended fertilizer doses led to significant increases in onion growth parameters (plant height, leaf area, biomass, and yield) and nutrient uptake (N, P, K, S). The highest nutrient uptake was observed when 100% of the recommended fertilizer dose was combined with *S. indica*, resulting in increases of up to 29.9% for nitrogen, 21.7% for phosphorus, 23.7% for potassium, and 23.4% for sulphur compared to fertilizer alone. PSB also played a crucial role in converting unavailable soil phosphorus into plant-available forms, further boosting nutrient acquisition and crop yield.

Microbial Bio stimulants and Plant Growth Promoting Bacteria (PGPB):

Novello et al. (2021) demonstrated that inoculation with PGPB strains increased onion plant growth and nutrient concentrations. Younes et al. (2023) showed that bio stimulants containing *Trichoderma album* and *Bacillus megaterium* improved onion growth, yield, and quality attributes under field conditions. Prisa and Altimari (2024) observed that the use of microorganisms and algae (GEA soil) in onion cultivation enhanced both growth and nutrient uptake, supporting the role of diverse microbial consortia as effective biofertilizers.

Farming System Context:

Galván et al. (2009) found that both organic and conventional farming systems in the Netherlands support diverse AMF communities within onion roots. This suggests that the beneficial effects of mycorrhizal associations are applicable across various farming systems and can play a significant role in enhancing nutrient cycling and overall plant health.

4.1.2 Effects of Beneficial Microorganisms on Onion Stress Tolerance

Drought Stress

Drought stress is a major constraint in onion production, leading to reduced vegetative growth, lower yields, and compromised bulb quality due to decreased photosynthetic activity and altered plant metabolism (Sansan et al. 2024). Galván et al. (2009) reported that AMF enhance soil structure by promoting soil aggregation, which improves water retention and root penetration, making plants more resilient to drought conditions. The extensive mycelial networks of AMF increase the soil volume accessible to onion roots, which is particularly important for onions due to their sparse root system. This allows onions to better acquire water and nutrients, especially under stress (Galván et al. 2009).

Pokluda et al. (2023) demonstrated that co-inoculation of AMF (*Rhizophagus irregularis*) with PGPM (e.g., *Azotobacter chroococcum*) in substrate formulations significantly boosted antioxidant activity (e.g., glutathione peroxidase) and reduced oxidative stress markers in onion seedlings. This acclimatization response was linked to improved root system functionality, enabling efficient mineral uptake even in degraded substrates.

Salinity Stress

El-Aal et al. (2024) reported that high salinity levels (from 0 to 4000 ppm NaCl) had a strong negative impact on onion growth and yield, reducing plant height, leaf number, bulb size, and overall biomass. However, when onions were treated with either *Pseudomonas putida* or endomycorrhizal fungi results that, significantly higher plant height, bulb diameter, and biomass than in uninoculated controls at both moderate and high salinity levels. The best results were seen when both microbes were used together. This combined treatment improved root colonization by mycorrhizae, boosted proline levels (proline being a key osmolyte that helps plants maintain cellular water retention and osmotic balance under salt stress), increased antioxidant activity, and helped the plants take up more potassium while maintaining ion balance. As a result, onions grown with both microbial treatments produced better yields and bulb quality, even under moderate and high salinity stress. Bulb yield increased by 3.5% at 0 ppm, 36% at 2000 ppm, and 83% at 4000 ppm NaCl compared to the non-inoculated control groups at the same salinity levels.

Disease Suppression

Galván et al. (2009) reported that AMF can help protect onions from soil-borne diseases by acting as a physical and biological barrier, outcompeting pathogens, and stimulating plant defence mechanisms.

Yağmur et al. (2024) found that AMF, especially the strain *Funneliformis mosseae*, and *Trichoderma harzianum* can effectively reduce the impact of Fusarium basal rot (FBR) in onions. This disease, caused by *Fusarium oxysporum* f. sp. *cepae*, is a major threat to onion crops. The study showed that using AMF not only reduced disease severity but also improved plant growth and phosphorus uptake. When AMF and *T. harzianum* were applied together, disease control and plant health improved even more. These effects are likely due to competition with harmful microbes, better nutrient absorption, and stronger plant defence systems. The study also found that resistance to FBR varies between onion varieties. Overall, the findings suggest that AMF and *T. harzianum* are promising tools for sustainable disease management in onions and could reduce the need for chemical fungicides.

Another research by Prestt and Roberts (2023) showed that controlling vascular wilt disease (so-called FBR) in onions, caused by *Fusarium oxysporum*, is closely linked to the composition of the soil fungal community rather than the bacterial one. In pot experiments, onions grown in naturally disease-suppressive soils had much lower disease levels. This suppressive effect could even be transferred by mixing suppressive soil with disease-prone soil, highlighting the role of the soil microbiome. Using high-throughput sequencing, the study found that certain beneficial fungal groups, such as *Gibellulopsis, Penicillium, Acremonium, and Pseudallescheria,* were associated with lower disease incidence. These fungi likely help by outcompeting or inhibiting the pathogen. The study suggests that promoting these beneficial fungi through practices like crop rotation or soil amendments could offer a sustainable and effective way to manage onion vascular wilt without relying on chemicals.

4.2 Farmer Survey

Question 1: What is the size of your onion cultivation area?

Results: Out of 13 respondents,

- 85% (11 farmers) reported cultivating onions on areas between 5 to less than 50 hectares.
- 15% (2 farmers) reported cultivating onions on areas between 100 to 500 hectares.
- No respondents reported cultivating onions on less than 5 hectares, 50 to less than 100 hectares, or more than 500 hectares.

Question 2: What type of farming system do you practice?

Results: Out of 13 respondents,

- 77% (10 farmers) practice conventional farming.
- 15% (2 farmers) practice organic farming.
- 8% (1 farmer) practice a mixed farming system.

Question 3: What soil management practices do you use? (Select all that apply)

Results: Out of 13 respondents,

- 100% (13 farmers) practice crop rotation
- 31% (4 farmers) practice cover cropping
- 23% (3 farmers) practice tillage reduction
- 8% (1 farmer) practice composting or organic amendments
- 0% no one practices mulching

Question 4:

(i) Have you heard about the role of microbiomes in plant growth and health?

Results: Out of 13 respondents,

- Yes : 69% (9 farmers)
- No : 31% (4 farmers)

(ii) If yes, where did you learn about microbiomes in agriculture? (Select all that apply)

Results: Out of 9 respondents who answered "Yes" to 4: (i),

- 67% (6 farmers) learn from agricultural training programs or workshops
- 56% (5 farmers) learn from extension services or advisors
- 44% (4 farmers) learn from academic or scientific publications
- 33% (3 farmers) learn from online resources or social media
- 22% (2 farmers) learn from fellow farmers or cooperatives

Question 5: How important do you think soil microbes are for onion cultivation?

Results: Out of 13 respondents,

- Very important: 69% (9 farmers)
- Somewhat important: 31% (4 farmers)
- Not important at all: 0%

Question 6: What do you believe are the biggest benefits of microbial activity in soil? (Select all that apply)

Results: Out of 13 respondents,

- 69% (9 farmers) - Improved nutrient availability for plants
- 69% (9 farmers) - Enhanced disease resistance
- 54% (7 farmers) - Better soil structure and aeration
- 54% (7 farmers) - Higher crop yields
- 54% (7 farmers) - Improved stress tolerance (e.g., drought, salinity)
- 39% (5 farmers) - Increased water retention
- 23% (3 farmers) - Reduced need for chemical fertilizers
- 23% (3 farmers) - Enhanced onion quality or nutritional value

Question 7:

(i) Do you use microbial inoculants (e.g., mycorrhizal fungi, rhizobacteria) in your farming?

Results: Out of 13 respondents,

- Yes : 15% (2 farmers)
- No : 85% (11 farmers)

(ii) If yes, what type of microbial inoculants do you use in your farming?

Results: Out of 2 respondents who use microbial inoculants,

- 100% (2 farmers) use plant growth-promoting bacteria
- No one use phosphate-solubilizing bacteria
- No one use commercial microbial inoculants

Question 8: How interested are you in learning more about or adopting microbiome-based technologies for your onion farming?

Results: Out of 13 respondents,

- 62% (8 farmers) are very interested
- 38% (5 farmers) are somewhat interested
- No one not interested
- No one already actively using microbiome technologies

Question 9: What are the biggest challenges you face in onion farming? (Select all that apply)

Results: Out of 13 respondents,

- 77% (10 farmers) - Weed control
- 54% (7 farmers) - Pest and disease control
- 54% (7 farmers) - Access to pesticides and herbicides
- 23% (3 farmers) - Water availability
- 15% (2 farmers) - Market prices
- 8% (1 farmer) - Climate variability
- 8% (1 farmer) - Access to quality seeds
- 8% (1 farmer) - High cost of inputs
- 8% (1 farmer) - Labor availability
- 8% (1 farmer) - Yield consistency/low productivity
- 0% (No farmer) - Soil fertility management
- 0% (No farmer) - Post-harvest losses

Question 10: What factors influence your decision to adopt new farming practices (microbiome-based practices)? (Select all that apply)

Results: Out of 13 respondents,

- 85% (11 farmers) - Recommendations from trusted sources (e.g., extension services)
- 62% (8 farmers) - Cost-effectiveness
- 54% (7 farmers) - Proven results from other farmers
- 23% (3 farmers) - Access to training or resources
- 15% (2 farmers) - Ease of implementation
- 0% (No farmer) - Environmental sustainability benefits

5. Discussion

5.1 Literature Review

5.1.1 Effects of Beneficial Microorganisms on Onion Plant Growth and Nutrients Uptake

The findings indicates that inoculation of beneficial microorganisms, whether through AMF, PSB, endophytic fungi, or PGPB, enhances onion growth and nutrient uptake. AMF and endophytic fungi extend the root system, increasing the soil volume explored and thus the absorption of water and nutrients, particularly in nutrient-depleted soils. PSB and certain fungi convert insoluble soil nutrients (especially phosphorus) into forms accessible to onions, overcoming a major limitation imposed by the crop's shallow root system (Arunachalam et al. 2024). Furthermore, microbial inoculation in combination with mineral fertilizers increases nutrient use efficiency, allowing for higher nutrient uptake and yield with the same or reduced fertilizer input (Novello et al. 2021; Arunachalam et al. 2024). PGPB and microbial bio stimulants enhance plant hormone production, root development, and stress tolerance, contributing to improved biomass accumulation and bulb quality (Novello et al. 2021; Younes et al. 2023).

These findings emphasize integrating beneficial microorganisms into onion cultivation offers a sustainable strategy to boost plant growth and nutrient uptake, reduce dependency on chemical fertilizers, and improve crop yield and quality.

5.1.2 Effects of Beneficial Microorganisms on Onion Stress Tolerance

The reviewed studies demonstrate that microbial inoculants play a critical role in increasing onion resilience to abiotic and biotic stressors. In drought-prone environments, AMF improve water uptake by enhancing soil aggregation and expanding root-soil contact zones through extensive mycelial networks (Galván et al. 2009). For onions, whose shallow root systems are naturally limited, this improved access to water can significantly reduce drought-related yield losses.

And also, antioxidant responses are commonly triggered in plants under drought stress as a defense mechanism against the buildup of reactive oxygen species

(ROS), which increase during water scarcity (Kesawat et al. 2023). The microbial inoculation improved root system functionality, enhancing both water and nutrient uptake under dry or degraded conditions. This suggests that the microbial consortium not only supported plant growth but also primed the plants' stress response systems, improving their physiological resilience to drought. The findings highlight the potential of targeted microbial inoculants to mitigate drought-induced oxidative damage and maintain metabolic balance in onion cultivation under water-limited conditions (Pokluda et al. 2023).

In saline conditions, microbial consortia such as *Pseudomonas* and AMF enhance plant tolerance by maintaining ionic balance and stimulating physiological responses like proline synthesis and antioxidant enzyme activity. These mechanisms reduce sodium toxicity and oxidative damage, enabling continued growth and bulb development even under salt stress (El-Aal et al. 2024).

Microorganisms associated with plants can play a vital role in boosting disease resistance by activating the plant's immune system and directly suppressing pathogens. Beneficial microbes trigger induced systemic resistance, producing defensive compounds and strengthening plant defences, while also competing with harmful pathogens in the soil. Harnessing these natural microbial interactions offers a sustainable way to protect crops and reduce dependence on chemical pesticides (Ali et al. 2023).

Together, these findings support the adoption of beneficial microorganisms through inoculating and enhancing practices as cost-effective and sustainable tools to mitigate drought, salinity, and disease pressures in onion cultivation.

5.2 Farmer Survey

Question 1: What is the size of your onion cultivation area?

Most of the onion farmers who took part in the survey run medium-sized commercial farms. About 85% grow onions on areas between 5 and 50 hectares, while around 15% grow on larger areas between 100 and 500 hectares. None of the farmers surveyed had very small or very large farms. The size of these farms may affect how easily they can use new methods like microbiome-based farming. Medium and large farms often have better access to new technology, but they may also be more careful about trying new things because they have more to lose. Knowing the size of the farms helps plan better support and advice for making onion farming more sustainable. Hu et al. (2022) reported that large scale farmers often have more money, workers, and equipment to invest in new ideas, and they can handle the risks better than smaller farms.

Question 2: What type of farming system do you practice?

Most of the onion farmers surveyed use conventional farming methods (77%). A smaller group uses organic farming (15%), and a mix of both (8%). These results show, conventional farming is common in farmers. The low number of organic or mixed farms could be due to challenges like higher costs, pest problems, and the need to produce consistent quality and quantity. Still, the few farmers using organic or mixed methods show that there is some interest in more sustainable ways of farming. This may affect how willing they are to try microbiome-based farming. Farmers using organic or mixed systems may be more open to using biological products and soil health practices. Support through advice and government programs could help more farmers shift toward sustainable and microbiome-friendly practices.

Question 3: What soil management practices do you use? (Select all that apply)

All surveyed farmers use crop rotation as a soil management practice. Crop rotation can break pest and disease cycles, helps manage soil fertility and reduce soil erosion (Nair and Delate 2016).

A smaller proportion of farmers use cover cropping (31%) and tillage reduction (23%). Cover crops can reduce soil erosion, enhance organic matter, weed suppression and support beneficial soil microbiota, (Nair and Delate 2016), but their adoption may be limited due to short growing seasons. Tillage reduction, while beneficial for soil structure and erosion control, is less common, possibly due to the need for fine seedbeds in onion production.

Only one respondent uses composting or organic amendments, and none reported using mulching. The low adoption of these practices may reflect the dominance of conventional farming systems among respondents, as well as challenges related to labor, costs, and the availability of organic materials. Mulching, although effective in moisture retention and weed suppression, may be less practical or less familiar in Swedish commercial onion systems.

Question 4:

(i) Have you heard about the role of microbiomes in plant growth and health?

The results show that, the majority of Swedish onion farmers heard about the role of microbiomes in plant growth and health. This relatively high level of awareness may reflect increased dissemination of microbiome-related knowledge in recent years. However, the fact that nearly one-third of respondents remain unaware highlights a persistent knowledge gap within the farming community. Bridging this gap is important for supporting the wider adoption of microbiome-based solutions, which could help improve soil health, reduce chemical inputs, and increase resilience to diseases and environmental stress.

(ii) If yes, where did you learn about microbiomes in agriculture? (Select all that apply)

Among the farmers who were familiar with microbiomes, the most common sources of information were agricultural training programs or workshops (67%) and extension services or advisors (56%). This highlights the key role that formal education plays in helping farmers learn about scientific topics like microbiomes. Some farmers also reported getting information from academic publications (44%) and online resources (33%), showing that a portion of the farming community actively looks for knowledge beyond traditional advice channels. Only a few respondents (22%) mentioned learning from other farmers or through cooperatives, which suggests that peer-to-peer learning, while helpful, is not the main way microbiome knowledge is shared in this group.

Question 5: How important do you think soil microbes are for onion cultivation?

Most of the Swedish onion farmers in the survey (69%) said that soil microbes are very important for onion cultivation, and the rest (31%) said they are somewhat important. Notably, the four farmers who had not heard of microbiomes were also the ones who considered microbes only somewhat important. None of the farmers thought microbes were not important at all. This result shows, that farmers widely recognize the important role of soil microbes in helping onions grow, take up nutrients, and disease suppression. However, since some farmers only rated microbes as somewhat important, it suggests, that there may be differences in how well farmers understand and apply microbiome management in practice. Overall, this is a good sign for the future. With more education and practical examples, farmers could gain more confidence and be more willing to use microbiome-based methods to support healthy and sustainable onion farming.

Question 6: What do you believe are the biggest benefits of microbial activity in soil? (Select all that apply)

The survey results indicate that Swedish onion farmers recognize a broad range of benefits associated with soil microbial activity. The most frequently cited benefits were improved nutrient availability for plants (69%) and enhanced disease resistance (69%). This reflects a strong awareness of the core functions of beneficial soil microbes, such as nutrient cycling and suppression of soil-borne pathogens, which are well-documented in scientific literature (Compant et al. 2019).

Over half of the respondents also identified better soil structure and aeration (54%), higher crop yields (54%), and improved stress tolerance (54%) as major benefits. These responses show that farmers appreciate the various role of soil microbes, not only in promoting plant health and productivity but also in enhancing soil physical properties and crop resilience to environmental stresses. Mycorrhizal fungi and microbial exudates like glomalin contribute to soil aggregation, enhancing soil porosity and aeration (Rillig, 2004). Furthermore, microbes such as *Bacillus* and *Pseudomonas* are known to help plants tolerate drought and salinity by regulating osmotic balance and producing stress-related enzymes and hormones (Vurukonda et al. 2016).

Fewer respondents selected increased water retention (39%), reduced need for chemical fertilizers (23%), and enhanced onion quality or nutritional value (23%). The lower selection of these options may farmers are aware of the direct agronomic benefits of microbial activity. However, the indirect or longer-term impacts-such as reduced input dependency and improved crop quality-are less widely recognized. Research shows that microbial inoculants can reduce fertilizer inputs while maintaining yield (Backer et al. 2018), and they may also influence crop nutritional content and flavor quality, particularly in horticultural crops (Calvo et al. 2014). Water retention, another crucial benefit linked to improved soil structure and organic matter, is also mediated by microbial metabolites and root-microbe interactions (Bender et al. 2016).

Overall, these findings suggest that Swedish onion farmers have a good foundational understanding of the benefits of soil microbes, particularly regarding nutrient availability and disease resistance. However, since the survey used predefined options, it is also possible that some responses were based on general assumptions or educated guesses. This highlights the importance of further engagement and education to ensure a deeper and more accurate understanding of microbial functions in agriculture.

Question 7:

(i) Do you use microbial inoculants (e.g., mycorrhizal fungi, rhizobacteria) in your farming?

The vast majority of surveyed Swedish onion farmers (85%) reported that they do not use microbial inoculants in their farming, with only 15% (2 farmers) indicating usage. Of these two, one practices organic farming and the other follows a conventional system, suggesting that interest in microbial inoculants exists across different production systems. Barriers to adoption may include lack of awareness, limited access to products, uncertainty about efficacy under local conditions, and cost considerations. These findings highlight the need for more farmer training, demonstration trials, and farmer education to promote the use of microbial inoculants.

(ii) If yes, what type of microbial inoculants do you use in your farming?

Among the few farmers who use microbial inoculants, all said they use plant growth-promoting bacteria. None reported using phosphate-solubilizing bacteria or commercial microbial mixes. This may show that farmers who try microbial products prefer simple, targeted options. It may due to familiarity, believe they work better, or can access them more easily. The fact that no one used commercial products might mean these are not widely available or that farmers are unsure about how useful they are for onion farming. These findings highlight the need for more extension services and field demonstrations to build confidence in a wider range of microbial technologies. And to illustrate their practical benefits for onion production.

Question 8: How interested are you in learning more about or adopting microbiome-based technologies for your onion farming?

The survey shows that Swedish onion farmers are very interested in microbiome-based technologies. About 62% said they are very interested, and 38% are somewhat interested in learning more or adopting microbiome-based technologies. Importantly, none of the farmers said they are not interested, and none are already actively using these technologies.

This strong interest may that farmers see the potential benefits, even though most have not yet started using these tools (Question 7:). The lack of current use shows there is a gap between interest and practice. These results match wider trends in farming, where more farmers are becoming curious about biological and ecological methods. Providing training, practical examples, and support could help turn this interest into real use of microbiome-based technologies in onion farming.

Question 9: What are the biggest challenges you face in onion farming? (Select all that apply)

The survey revealed that the most commonly reported challenge among Swedish onion farmers is weed control (77%), followed by pest and disease control (54%) and access to pesticides and herbicides (54%). These results highlight the ongoing struggle with both biological threats and the tools needed to manage them effectively. Access to pesticides and herbicide may be problematic due to regulatory restrictions, rising costs, and the risk of resistance development. Other concerns included water availability (23%) and market prices (15%), while issues like climate variability, access to quality seeds, high cost of inputs, labour availability and yield consistency were each reported by a smaller share of respondents. Notably, no farmers selected soil fertility management or post-harvest losses as major concerns.

Overall, these findings suggest that Swedish onion farmers are primarily challenged by weed, pest and disease management, as well as by the availability and cost of agrochemicals. This underscores the need for integrated weed and pest management strategies, greater access to effective and sustainable crop protection products, and the potential value of microbiome-based or biological solutions to reduce reliance on chemicals.

Question 10: What factors influence your decision to adopt new farming practices (microbiome-based practices)? (Select all that apply)

The most influential factor in farmers' decisions to adopt new farming practices (microbiome-based) is recommendations from trusted sources (85%), such as extension services. This underscores the critical role that extension agents, advisors, and other authoritative sources play in the diffusion of agricultural innovations.

Cost-effectiveness (62%) and proven results from other farmers (54%) are also major drivers, indicating that economic considerations and peer experiences are highly valued. Farmers seek evidence that new practices will deliver tangible financial benefits and prefer to see successful outcomes in similar local contexts before making changes themselves. This highlights the importance of on-farm trials, demonstration plots, and farmer-to-farmer knowledge exchange in promoting adoption.

Access to training or resources (23%) and ease of implementation (15%) were less frequently cited. This suggesting, while these factors matter, they are not as decisive as trusted recommendations and cost-effectiveness. Notably, environmental sustainability benefits were not selected by any respondent, indicating that, in this group, environmental motivations are secondary to practical and economic considerations when deciding whether to adopt microbiome-based or other innovative practices.

Methodological Reflection:

While the structured questionnaire used in this study provided useful insights into farmers' awareness of beneficial microorganisms, several limitations were noted. The fixed-choice format limited the depth of responses and may have influenced how farmers interpreted and selected answers.

Moreover, cross-question analysis (e.g., comparing those who rated microbes as important with their familiarity or farming method) highlighted the value of linking responses across questions, which could be enhanced with more precise demographic tagging or follow-up questions. In future studies, combining the survey with in-depth interviews would allow for a better understanding of how individual farmers perceive microbial technologies, their barriers to adoption, and their current agronomic strategies.

The variation in how the survey was administered, some in person and others digitally. It may have influenced the depth and clarity of responses. This discrepancy could have affected the comparability of data, as in-person participants had more opportunity to seek clarification or provide nuanced feedback, unlike those responding via Google Form.

5.3 Overall Discussion

The combined insights from the literature review and the farmer survey provide a comprehensive understanding of the current state, potential, and challenges of microbiome-based approaches in onion cultivation.

Literature studies clearly demonstrate that beneficial microorganisms, including AMF, PSB, endophytic fungi, and PGPB, play an important role in enhancing onion growth, nutrient uptake, and resilience to biotic and abiotic stresses. AMF and endophytes expand the functional root zone, improving nutrient and water absorption (Galván et al. 2009; Shuab et al. 2014). PSB convert insoluble phosphorus into bioavailable forms, addressing a key limitation in onion nutrition (Khan et al. 2009; Arunachalam et al. 2024). Microbial biostimulants and PGPB further support plant health by promoting hormone production, root development, and stress tolerance, leading to improved yield and bulb quality (Backer et al. 2018; Novello et al. 2021).

These results are supported by research on other crops. In maize and wheat, microbial consortia have enhanced nitrogen-use efficiency, drought tolerance, and disease resistance (Saravanakumar et al. 2017; Li et al. 2021; Matsumoto et al. 2021). In rice, endophytes and rhizobacteria have been used to suppress seedling blight and increase antioxidant capacity (Matsumoto et al. 2021). These examples reinforce that the mechanisms observed in onions are part of a broader trend across crop systems and thus provide a solid scientific basis for expanding application of beneficial microorganisms in Swedish horticulture.

The farmer survey shows that Swedish onion growers are interested in using microbiome-based practices, but they are still careful and unsure because they don’t have much experience with them yet. Most surveyed farmers operate medium to large commercial farms. Majority of the farmers practiced conventional methods, though there is some interest in organic and mixed systems. All of the surveyed farmers practiced crop rotation, but other soil health practices like cover cropping, tillage reduction, and composting are less common, potentially limiting the natural buildup of beneficial soil microbiota. Encouragingly, there is a relatively high level of awareness about the role of microbiomes in plant health, with the majority of farmers recognizing soil microbes as very important for onion cultivation. Farmers primarily learn about microbiomes through formal channels such as training programs and extension services, indicating a reliance on expert guidance for new technologies. However, practical adoption of microbiome-based products remains low, with only a small fraction of farmers currently using microbial inoculants. This is consistent with global trends, where farmers often hesitate to adopt microbial products due to limited product availability, mixed field performance, or lack of local research data (Tensi et al. 2022).

Hansson (2025), observations align with both current research and practical challenges in microbiome management for onion cultivation. There is indeed a growing awareness among farmers about the importance of microbiomes but many remain unsure about the extent of their benefits. The best ways to promote them especially in regions like southern Sweden where organic amendments are scarce due to few animal farms. Scientific studies confirm that organic amendments, such as compost, can significantly boost soil microbial diversity and function, but their availability and use are limited in some areas (Ros et al. 2006).

Globally, some farmers address soilborne disease by sterilizing soil with chemicals like methyl sodium, then reintroducing beneficial microbes to restore a healthy rhizosphere. Research shows that while sterilization can eliminate both pathogens and beneficial microbes, subsequent inoculation or crop growth can help re-establish a balanced microbial community, sometimes even enhancing plant growth and beneficial bacteria recruitment. Sterilization also, help to control weed (Razavi and Lakzian 2007).

Hansson (2025) also notes that, despite extensive research on mycorrhizal fungi, field trials with commercial mycorrhizal products in high-input systems have often yielded inconsistent results. This may be due to competition with native soil microbiota or the suppressive effects of high fertilizer rates on symbiotic relationships. At the same time, the rise of soilborne diseases like Fusarium in northern Europe and the US, exacerbated by climate extremes, highlights the need to create environments where beneficial microbiomes can thrive and support disease suppression. Approaches such as reduced tillage and drip irrigation (which can deliver bio stimulants like Trichoderma directly to the root zone) are promising but can be challenging to implement in practice. Ongoing trials in Borgeby are testing these methods.

Impact of Beneficial Microorganisms on Society

Integrating beneficial microorganisms into onion cultivation may positively affect to the society. For growers, the use of beneficial microorganisms, such as PGPM, mycorrhizal fungi, and bio stimulants can reduce reliance on synthetic fertilizers and pesticides, leading to lower input costs (Backer et al. 2018). For consumers, microbiome-based practices can contribute to safer and healthier food by minimizing chemical residues on produce (Calvo et al. 2014).

In advance, these practices can benefit society by promoting more sustainable agriculture, reducing environmental pollution, and supporting the long-term health of soils and ecosystems. Ultimately, healthier soils and reduced chemical use can contribute to improved public health.

Impact of Beneficial Microorganisms on the Environment

The use of beneficial microorganisms in agriculture offers important environmental benefits, particularly in reducing the ecological footprint of crop production. By decreasing the need for synthetic fertilizers and pesticides, microbiome-based technologies contribute to improved soil health, increased organic matter content, and restored biological activity in degraded soils (Lazcano et al. 2013; Compant et al. 2019). These effects are especially valuable in intensive systems like onion cultivation, where high input use often leads to soil degradation and nutrient imbalances. Furthermore, use of beneficial microorganisms may reduce the use of agrochemicals and it helps protect nearby waterbodies by reducing the runoff of agrochemicals. It may also, promote above ground and belowground biodiversity.

Impact of Beneficial Microorganisms on United Nations Sustainable Development Goals (SDGs)

- SDG 2: Zero Hunger

Microbiome innovations improve soil health and crop productivity, supporting sustainable food production and food security for growers and consumers.

- SDG 6: Clean Water and Sanitation

Reducing agrochemical runoff through microbiome management protects water bodies from contamination and supports clean water initiatives

- SDG 12: Responsible Consumption and Production

By reducing the need for chemical fertilizers and pesticides, microbiome-based practices promote more efficient resource use and minimize environmental pollution, leading to safer and more sustainable food systems.

- SDG 13: Climate Action

Enhancing soil health increases soil carbon storage and reduces greenhouse gas emissions, helping agriculture adapt to and mitigate climate change.

(THE 17 GOALS | Sustainable Development, n.d.)

6. Conclusion

This study demonstrates that integrating beneficial microorganisms, such as arbuscular mycorrhizal fungi (AMF), phosphorus-solubilizing bacteria (PSB), endophytic fungi, and plant growth-promoting bacteria (PGPB) into onion cultivation can significantly improve plant growth, nutrient uptake, stress tolerance, and disease resistance. Literature findings confirm that these microbes enhance onion performance by improving root function, nutrient efficiency, and resilience to drought, salinity, and soil-borne diseases. The farmer survey shows that Swedish onion growers are increasingly aware of the importance of soil microbes, but practical adoption of microbiome-based practices remains limited due to knowledge gaps and resource constraints. Overall, microbiome management offers a promising, sustainable path for boosting onion yield and quality, but wider adoption will require more education, demonstration, and support for growers.

7. Future Recommendations

1) Expand Farmer Education and Training

Enhance outreach through workshops, extension services, and demonstration farms to close the knowledge gap about microbiome management and its practical benefits in onion cultivation.

2) Promote On-Farm Trials and Demonstrations

Support participatory research and on-farm trials to showcase the effectiveness of microbial inoculants and soil health practices under local conditions, helping farmers gain confidence in adopting these innovations.

3) Develop Regionally Adapted Microbial Products

Encourage research and development of microbial inoculants tailored to the specific soil, climate, and farming systems in Sweden. Focus on combinations of arbuscular mycorrhizal fungi (AMF), phosphorus-solubilizing bacteria (PSB), endophytic fungi, and plant growth-promoting bacteria (PGPB) that are effective in local high-input systems.

4) Monitor Environmental and Societal Impacts

Continue to assess the broader impacts of microbiome-based practices on soil health, water quality, biodiversity, and food safety, ensuring that these innovations align with sustainability goals and societal expectations.

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Popular science summary

Onions are one of the most important vegetables in the world and are widely grown in Sweden. However, growing onions may challenge because of climate change, plant diseases, and poor soil health. These problems make it harder for farmers to achieve optimal yields and can also harm the environment.

Scientists have discovered that tiny living things called "microbiomes"-which include helpful bacteria and fungi, can support plants in many ways. These microbes live on and around onion roots and leaves. They help onions get nutrients from the soil, protect them from diseases, and make them stronger against stresses like too much water or too less water, as well as nutrients. Using microbiomes could mean farmers need fewer chemical fertilizers and pesticides, making onion farming better for the environment.

Most research on plant microbiomes has focused on crops like wheat and rice. There is much less information about how microbiomes help onions. To learn more, my thesis reviews what scientists have found about microbiomes in onion farming and also includes interviews with Swedish onion farmers to see how much they know about these helpful microbiomes.

The results show that while science supports the benefits of microbiomes, many Swedish onion farmers are not yet using them or may not know about their potential. Teaching farmers about microbiomes and how to use them could make onion farming more productive and sustainable, helping both people and the planet.

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I am profoundly grateful to my husband for his unwavering support, patience, and understanding throughout this process. His love and encouragement have been my greatest strength.

Finally, my deepest gratitude goes to my parents, family members and friends for their unconditional support and love throughout my life and my studies.

Appendix 1: Questionnaire

Section 1: General Farming Information

1. What is the size of your onion cultivation area?

   ◯ Less than 5 hectares
   ◯ 5 to less than 50 hectares
   ◯ 50 to less than 100 hectares
   ◯ 100 to 500 hectares
   ◯ More than 500 hectares
   ◯ Other (please specify): …………………………

2. What type of farming system do you practice?

   ◯ Conventional
   ◯ Organic
   ◯ Mixed
   ◯ Other (please specify): …………………………

3. What soil management practices do you use? (Select all that apply)

   ◯ Crop rotation
   ◯ Cover cropping
   ◯ Composting or organic amendments
   ◯ Mulching
   ◯ Tillage reduction
   ◯ Other (please specify): …………………………

Section 2: Awareness and Perceptions of Microbiomes

4. (i) Have you heard about the role of microbiomes in plant growth and health?

◯ Yes
◯ No

(ii) If yes, where did you learn about microbiomes in agriculture? (Select all that apply)

◯ Agricultural training programs or workshops
◯ Fellow farmers or cooperatives
◯ Online resources or social media
◯ Academic or scientific publications
◯ Extension services or advisors
◯ Other (please specify): …………………………

5. How important do you think soil microbes are for onion cultivation?

◯ Not important at all
◯ Somewhat important
◯ Very important

6. What do you believe are the biggest benefits of microbial activity in soil? (Select all that apply)

◯ Improved nutrient availability for plants
◯ Enhanced disease resistance
◯ Better soil structure and aeration
◯ Increased water retention
◯ Reduced need for chemical fertilizers
◯ Improved stress tolerance (e.g., drought, salinity)
◯ Enhanced onion quality or nutritional value
◯ Higher crop yields
◯ Other (please specify): …………………………

7. (i) Do you use microbial inoculants (e.g., mycorrhizal fungi, rhizobacteria) in your farming?

◯ Yes
◯ No

(ii) If yes, what type of microbial inoculants do you use in your farming?

- ◯ Mycorrhizal fungi
- ◯ Plant growth-promoting bacteria
- ◯ Phosphate-solubilizing bacteria
- ◯ Commercial microbial inoculants
- ◯ Other (please specify): …………………………

8. How interested are you in learning more about or adopting microbiome-based technologies for your onion farming?

- ◯ Not interested
- ◯ Somewhat interested
- ◯ Very interested
- ◯ Already actively using microbiome technologies

Section 3: Practices and Challenges

9. What are the biggest challenges you face in onion farming? (Select all that apply)

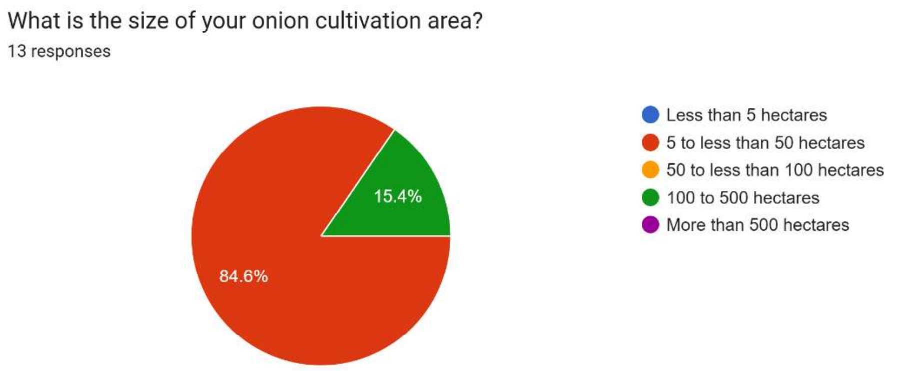
- ◯ Pest and disease control
- ◯ Weed control
- ◯ Soil fertility management
- ◯ Climate variability
- ◯ Water availability
- ◯ Access to quality seeds
- ◯ Access to pesticides and herbicides
- ◯ High cost of inputs
- ◯ Labor availability
- ◯ Yield consistency/ low productivity
- ◯ Market prices
- ◯ Post-harvest losses
- ◯ Other (please specify): ……………………………

10. What factors influence your decision to adopt new farming practices (microbiome-based practices)? (Select all that apply)

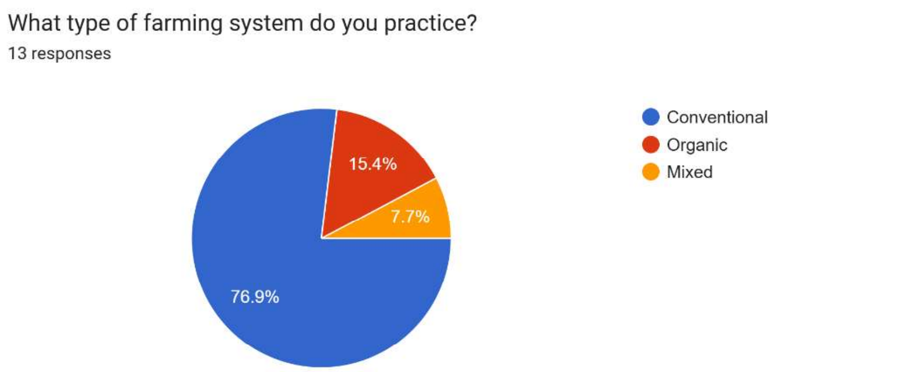
- ◯ Cost-effectiveness
- ◯ Ease of implementation
- ◯ Recommendations from trusted sources (e.g., extension services or advisors)
- ◯ Proven results from other farmers
- ◯ Access to training or resources
- ◯ Environmental sustainability benefits
- ◯ Other (please specify): ……………………………

Appendix 2: Results of the Survey

Question: 1



Question: 2



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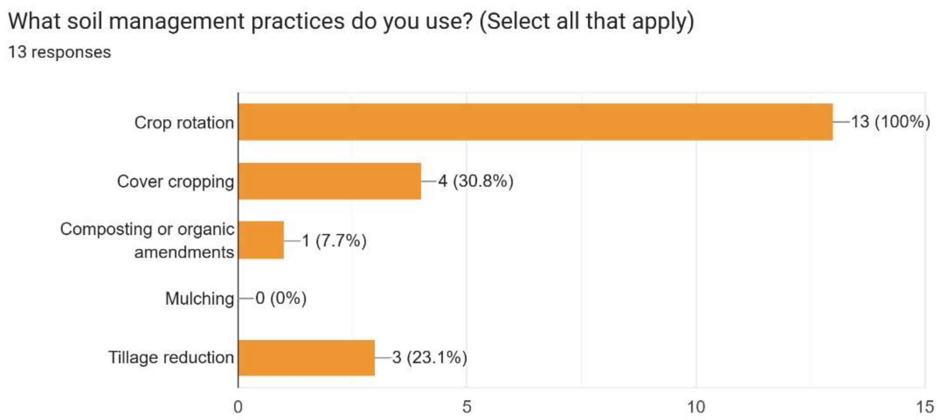
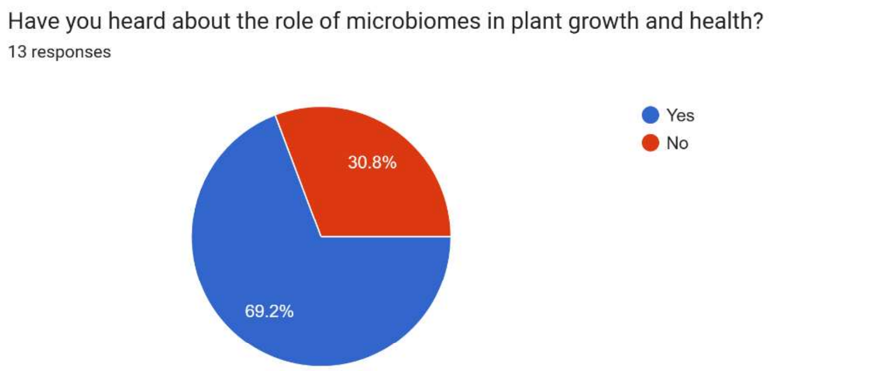
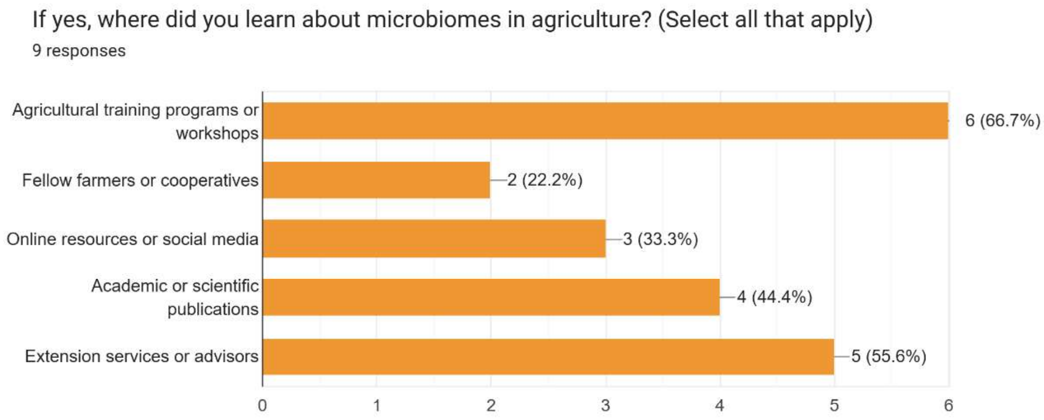


Question: 4

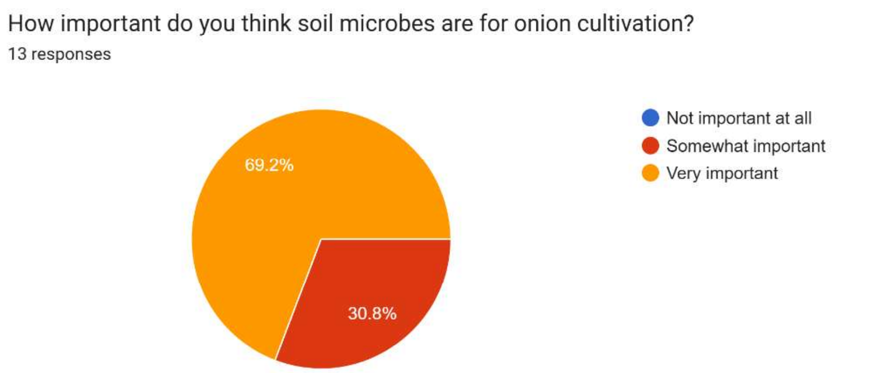
(i)



(ii)

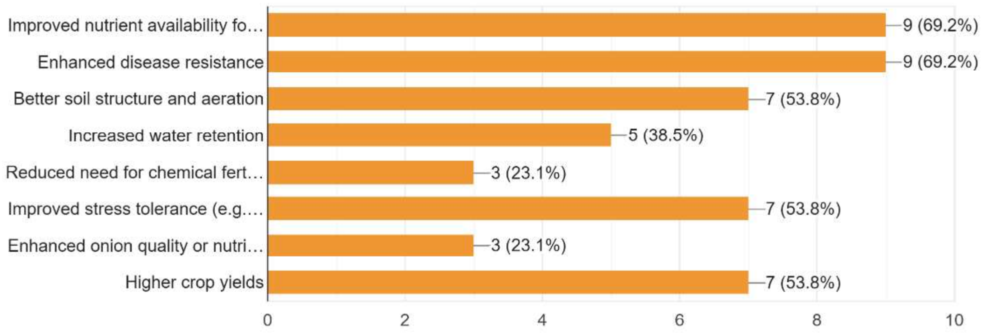


Question: 5



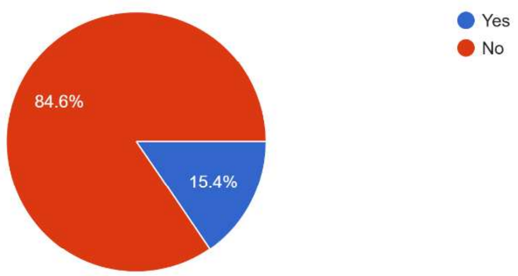
Question: 6

What do you believe are the biggest benefits of microbial activity in soil? (Select all that apply)
13 responses



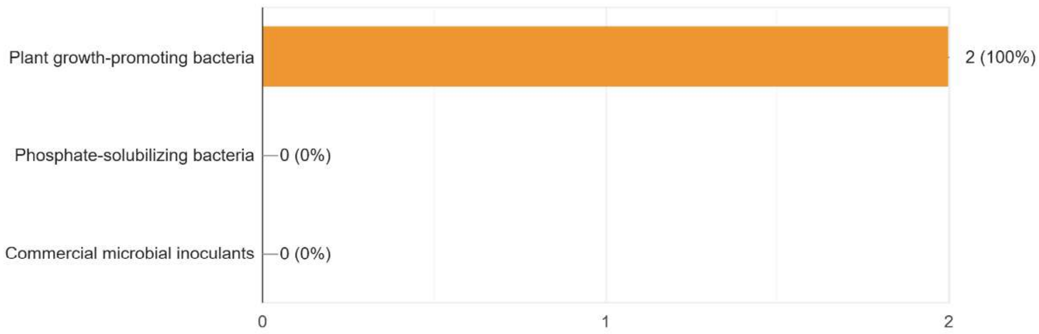
Question: 7
(i)

Do you use microbial inoculants (e.g., mycorrhizal fungi, rhizobacteria) in your farming?
13 responses



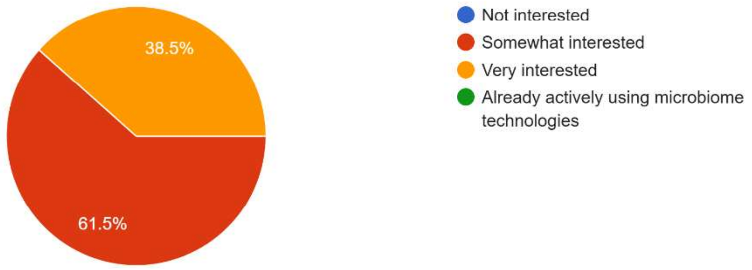
(ii)

If yes, what type of microbial inoculants do you use in your farming?
2 responses



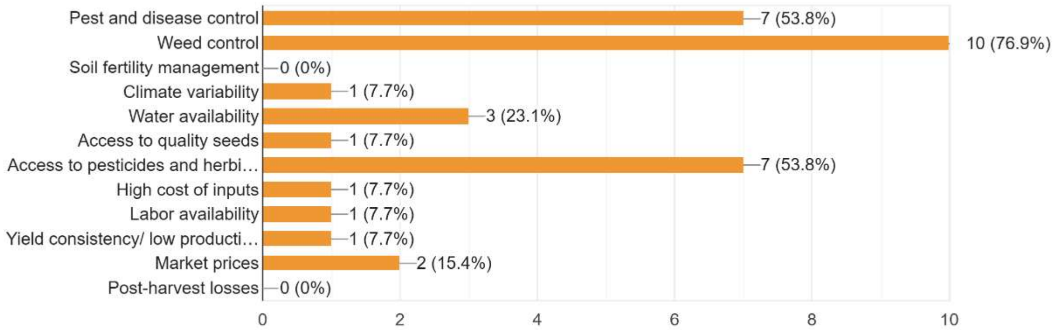
Question: 8

How interested are you in learning more about or adopting microbiome-based technologies for your onion farming?
13 responses



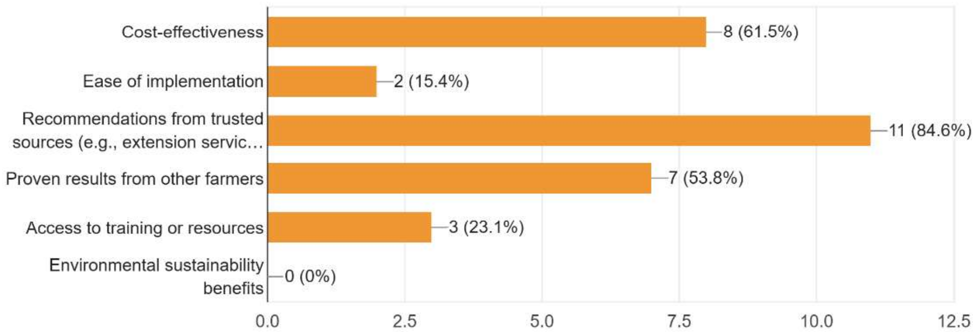
Question: 9

What are the biggest challenges you face in onion farming? (Select all that apply)
13 responses



Question: 10

What factors influence your decision to adopt new farming practices (microbiome-based practices)? (Select all that apply)
13 responses



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