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Crucial role of fungi in environmentally sustainable agriculture

Papel crucial dos fungos na agricultura ambientalmente sustentável

Papel crucial de los hongos em la agricultura ambientalmente sostenible

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ABSTRACT
To produce more, better and safer food we must be able to do so while promoting the sustainable use of agricultural resources. The increase in agricultural production is currently through the use of pesticides, fertilizers, and developments in plant breeding and genetic skills. In naturally existing ecosystems, rhizospheric soils have biological living beings to favor the plant development, nutrient assimilation, stress tolerance, disease deterrence, carbon seizing and others. Fungi are among the most widely distributed organisms on Earth and are of great environmental importance. Mycorrhizal fungi, bacteria, actinomycetes, etc. solubilize nutrients and assist the plants in uptake by roots. Amongst them, vesicular/arbuscular mycorrhizal fungi (AMF) have key roles in the natural ecosystem, as the majority of the terrestrial plants form association with AMF. This symbiosis confers benefits directly to the host plant's growth and development through the acquisition of phosphorus (P) and other mineral nutrients from the soil. They may also enhance the protection of plants against pathogens, increase plant diversity and have the potential to enhance plant growth under stressful environments. In this article, the sustainability and environmental aspects of agriculture, and the basic concepts of fungi will be reviewed to justify our point of view about the tremendous importance of fungi towards an environmentally sustainable agriculture.

Keywords: fungi, arbuscular mycorrhizal fungi, sustainable agriculture, environment.

RESUMO
Para produzir mais, melhores e mais seguros alimentos, temos de ser capazes de o fazer, promovendo simultaneamente a utilização sustentável dos recursos agrícolas. O aumento da produção agrícola actualmente ocorre através da utilização de pesticidas, fertilizantes e desenvolvimentos no melhoramento de plantas e competências genéticas. Nos ecossistemas naturalmente existentes, os solos rizosféricos possuem seres vivos biológicos para favorecer o desenvolvimento das plantas, a assimilação de nutrientes, a tolerância ao estresse, a dissuasão de doenças, a apreensão de carbono e outros. Os fungos estão entre os organismos mais amplamente distribuídos na Terra e são de grande importância ambiental. Fungos micorrízicos, bactérias, actinomicetos, etc. solubilizam nutrientes e auxiliam na absorção das plantas pelas raízes. Entre eles, os fungos micorrízicos vesiculares/arbusculares (FMA) desempenham papéis fundamentais no ecossistema natural, uma vez que a maioria das plantas terrestres se associam aos FMA. Esta simbiose confere benefícios diretamente ao crescimento e desenvolvimento da planta hospedeira através da aquisição de fósforo (P) e outros nutrientes minerais do solo. Podem também mejorar

la protección de las plantas contra agentes patogénicos, aumentar a diversidade e tem potencial de melhorar o crescimento de plantas em ambientes estressantes. Neste artigo, a sustentabilidade e os aspetos ambientas da agricultura e os conceitos básicos dos fungos serão revistos para justificar nosso punto de vista sobre a tremenda importância dos hongos para una agricultura ambientalmente sustentável.

Palabras-chave: fungos, fungos micorrízicos arbusculares, agricultura sustentável, ambiente.

RESUMEN
Para producir más alimentos, mejores y más seguros, debemos poder hacerlo promoviendo al mismo tiempo el uso sostenible de los recursos agrícolas. El aumento de la producción agrícola se debe actualmente al uso de pesticidas, fertilizantes y al desarrollo de técnicas genéticas y de fitomejoramiento. En los ecosistemas existentes naturalmente, los suelos rizosféricos cuentan con seres vivos biológicos para favorecer el desarrollo de las plantas, la asimilación de nutrientes, la tolerancia al estrés, la disuasión de enfermedades, la captación de carbono y otros. Los hongos se encuentran entre los organismos más ampliamente distribuidos en la Tierra y tienen una gran importancia ambiental. Hongos micorrízicos, bacterias, actinomicetos, etc. solubilizan los nutrientes y ayudan a las plantas a absorberlos por las raíces. Entre ellos, los hongos micorrízicos vesiculares/arbusculares (HMA) desempeñan funciones clave en el ecosistema natural, ya que la mayoría de las plantas terrestres forman asociaciones con HMA. Esta simbiosis confiere beneficios directamente al crecimiento y desarrollo de la planta huésped mediante la adquisición de fósforo (P) y otros nutrientes minerales del suelo. También pueden mejorar la protección de las plantas contra patógenos, aumentar la diversidad de las plantas y mejorar el crecimiento de las plantas en ambientes estresantes. En este artículo se revisarán los aspectos medioambientales y de sostenibilidad de la agricultura, y los conceptos básicos de los hongos para justificar nuestro punto de vista sobre la tremenda importancia de los hongos hacia una agricultura ambientalmente sostenible.

Palabras clave: hongos, hongos micorrízicos arbusculares, agricultura sustentable, ambiente.

1 INTRODUCTION

The Food and Agricultural Organisation (FAO) has traditionally focused on agricultural productivity, exemplified by the allocation of its regular programme budget. But recently expanded it, adopting a more integrated, multi-faceted approach, often captured by the term “food systems” (Emadi and Rahmanian, 2020). To grow well, plants need a wide range of nutrients in various amounts, depending on the individual plant and its stage of growth. The three key plant nutrients usually derived from soil are nitrogen, phosphorus and potassium, while carbon, oxygen and hydrogen are absorbed from the air. Other vital soil nutrients include magnesium, calcium and sulphur.

In naturally existing ecology, rhizospheric soils contain biological living beings to favor the plant development, nutrient assimilation, stress tolerance, disease deterrence, carbon seizing and more. These organisms include mycorrhizal fungi, bacteria, actinomycetes, etc. which solubilize nutrients and assist the plants in uptake through roots.

In this article, the role of fungi in environmentally sustainable agriculture will be examined, as in our opinion, that role is crucial and fungi deserve much more prominence in discussions over our future on Earth. Fungi are metabolic masters, earth makers and key players in most life processes (Sheldrake, 2020). The results of research into the properties of fungi, their uses, benefits and special characteristics seem to position the world of fungi as the next agent of change worldwide, becoming another pillar in promoting a historic environmental revolution in our society. Food production, contribution to climate change and the potential to combat numerous diseases are among the ways in which fungi could make a significant impact.

2 THEORETICAL FRAMEWORK

The theoretical framework in the present study, where our viewpoint is presented, comprises an analysis of data on the sustainability and environmental aspects of agriculture, previous relevant research on fungus topics, to finally arrives to present our opinion about the role of fungi in agriculture sustainability.

3 SUSTAINABILITY AND ENVIRONMENTAL ASPECTS OF AGRICULTURE

The FAO mandate is to “improve nutrition, increase agricultural productivity, raise the standard of living in rural populations and contribute to global economic growth”. According to that, FAO surveyed and published the systematic growth of international agriculture. Between 2000 and 2021, agricultural land declined by 86 million ha while forest area declined by 104 million ha. Half of all harvested land is planted with cereals. Data from FAO.org shows the evolution of the production of primary crops from 2000 until 2021. There was an increase of 54% in primary crop production in that period, representing around 9.5 billion tonnes in 2021, maintaining Europe and the Americas as larger exporters and Asia as the primary importer in the cereal trade. The report also described an increase of 84% in agricultural value added in that period, although its share of 4% in global Gross Domestic Product (GDP) remained stable.

It is well known that soil health management is crucial for ensuring sustainable agricultural productions and the maintenance of biodiversity. Fertilizers and pesticides are a necessary evil for industrial agriculture. Although they continue to be critically important tools for global food security, their undesirable effects cannot be overlooked particularly when sustainable agriculture is the universal focus. Apart from a range of widely discussed and well-known adverse effects of chemical fertilizers and pesticides on environment and human health they have also been held responsible for strongly influencing the microbial properties of soil.

Soil microflora is a key component of agricultural ecosystems that not only plays a significant role in the basic soil processes but is also actively involved in enhancing soil fertility and crop productivity. Microbial activity in soil has a strong impact on its physical properties and is simultaneously instrumental in pursuing eco-friendly practices such as bioremediation and biocontrol of phytopathogens in agricultural soils. Soil microorganisms have thus been accepted as bioindicators of soil health and activity.

Fertilizers and pesticides tend to persist in soil for long periods and are thus bound to affect the soil microflora thereby disturbing soil health. Amendment of soil with fertilizers and pesticides strongly influences a range of soil functions and properties like rhizodeposition, nutrient content of bulk and rhizospheric soil, soil organic carbon, pH, moisture, activities of soil enzymes and many others. All these factors indirectly lead to a shift in the population dynamics of soil microflora along with the direct effects of fertilizers and pesticides such as toxicity and altered substrate availability profile of the soil. Though such effects are variable depending on many biotic and abiotic factors ranging from soil characteristics to crop variety, it has been well established that long term and excessive chemical inputs in soil undoubtedly influence the soil microbial communities in terms of their structural and functional diversity as well as the dominant soil species.

The augmentation in agricultural production seen in the present century is due mainly to the progress and use of pesticides, fertilizers containing nitrogen and phosphorus, and developments in plant breeding and genetic skills (Prashar and Shah, 2016). The aforementioned FAO report includes an approximate calculation about fertilizer and pesticide use. In 2021 the use of inorganic fertilizers in agriculture was around 195 million tons of nutrients, 56% of which was nitrogen. Pesticide use went up 62% between 2000 and 2021, with the Americas accounting for half of total usage in 2021. The greenhouse gas emissions from agrifood systems increased 10% while the farm-gate greenhouse gas emissions went up 14% from 2000 to 2021. It is evident that the present situation is unsustainable and must be modified to achieve a proper environmentally sustainable agriculture.

Sustainable agricultural practices are intended to protect the environment, expand the Earth's natural resource base, and maintain and improve soil fertility through a range of production practices, conventional and organic. A regionally integrated system of plant and animal production practices must be designed to produce long-term results such as: production of sufficient human food, feed, fiber, and fuel to meet the needs of a rising population; protection of the environment and expansion of the natural resources supply; sustainment of the economic viability of agriculture systems. Thus, efficient plant nutrition management should ensure both enhanced and sustainable agricultural production and safeguard the environment.

4 FUNGI

4.1 DEFINITIONS AND BASICS CONCEPTS

A fungus, (plural fungi), is an organism with a nucleus, spore-bearing, achlorophyllous, that generally reproduce sexually and asexually, and whose somatic structures, usually filamentous and branched, are typically surrounded by a cell wall containing cellulose or chitin, or both (Alexopoulos, 1964). Fungi are also any of about 144,000 known species of organisms of the kingdom Fungi, which includes the yeasts, rusts, smuts, mildews, molds, and mushrooms. There are also many fungus like organisms, including slime molds and oomycetes (water molds), that do not belong to kingdom Fungi but are often called fungi. Many of these fungus like organisms are included in the kingdom Chromista.

Fungi are among the most widely distributed organisms on Earth and are of great environmental and medical importance. Many fungi are free-living in soil or water; others form parasitic or symbiotic relationships with plants or animals (E. Britannica). By another definition, fungus is any member of the group of eukaryotic organisms that includes microorganisms such as yeasts and molds, as well as the more familiar mushrooms (Wikipedia). These organisms are classified as one of the traditional eukaryotic kingdoms, along with Animalia, Plantae and either Protista or Protozoa and Chromista. Many people mistakenly believe fungi are plants, however, fungi are neither plants nor animals but rather organisms that form their own kingdom of life. The way they feed themselves is different from other organisms: they do not photosynthesize like plants and neither do they ingest their food like animals. Fungi actually live inside their food and secrete enzymes to dissolve nutrients they then absorb. Fungi rank third among the major kingdoms in terms of known taxa, with approximately 155,000 species scientifically documented to date. Animals number 1.45 million and plants 345,000–390,000. Estimated global species richness varies considerably among these three kingdoms and between authors.The most current figures given here suggest that a large proportion of plant species (80–85%) is likely already known, whereas the full diversity of animals, particularly invertebrates (less than 20% known), and fungi (less than 5–10% known) remains largely undescribed (Antonelli et al., 2020; Niskanen et al., 2023; Index Fungorum Partnership, 2023).

Certain fungi, such as yeast, multiply by sprouting. However, most fungi form networks of many cells known as hyphae: fine tubular structures that branch, merge and intertwine, forming an anarchic filigree of mycelium. The mycelium represents a more common habit of fungi and can be better understood not as a thing but as a process, an irregular and exploratory tendency. Water and nutrients flow through ecosystems within the mycelial networks. The mycelium of some fungal species is excitable and conducts waves of electrical activity along the hyphae, analogous to electrical impulses in the nerve cells of animals. Recent findings suggest that fungal mycelia can 'recognize' shapes (Fukasawa *et al*., 2024). Anyway, our comprehension of the mysterious world of fungi is limited, especially when compared to our knowledge of plants and animals.

Fungi, by reason of their ubiquity and surprisingly large number, play a very important role in the slow but constant modifications that take place around us. Specifically, fungi are the agents responsible for a large part of the decomposition of organic substances and as such, they affect us directly through the destruction of food, tissues, etc. They cause most plant diseases and also many diseases of animals and man; they constitute the basis of a number of industrial fermentation processes, such as the production of bread, wine, beer, the fermentation of plant seeds, cocoa, and the preparation of certain cheeses. They are used in the commercial production of many organic acids and some vitamin preparations and are responsible for the manufacture of certain antibiotic drugs, among which penicillin stands out.

Fungi can be harmful or beneficial for agriculture. The breakdown of plant materials is made primarily by secreted fungal enzymes. Driven by the urge for non-food based bioenergy, industrial scale conversion of biowaste has been researched and developed for some years with a key role of fungi in the composting system. Fungi are extraordinary decomposers of organic waste material and most readily attack cellulose, lignins, gums, and other organic complex substances. Fungi can also act under a wide range of soil reactions from acidic to alkaline soil reactions. The most efficient and gentle way of converting recalcitrant lignocellulosic materials for industrial purposes is through the use of fungal enzymes. The building blocks of the organic materials are kept intact, ready to use in the value cascade. The enzymatic conversion of biowaste and –sidestreams can provide the basis for a new way for more efficient use of natural resources, paving the way for a larger bioeconomy sector in a more biobased society.

As fungi can damage crops, causing losses of millions of dollars due to the diseases they produce in the plantations, on the other hand, they are able to increase the fertility of the soil due to the various changes they cause, which usually result in the production of nutrients that are used by green plants. As it is possible to cultivate in test tubes, fungi are special material for studies of fundamental biological processes. They do not have stems, roots or leaves, nor do they have a developed vascular system like the most evolved plant types. They are, in general, filamentous and multicellular, their nuclei can be observed with relative ease; their somatic structures, with some exceptions, show little differentiation and virtually no division of labor. The filaments that constitute the body of a fungus elongate by apical growth, but most of the organism is potentially capable of growth, and a small fragment of any part of the fungus is sufficient to start a new individual.

Reproductive structures of fungi are differentiated from somatic structures and exhibit a variety of forms that are use for classification. Few fungi can be identified if their reproductive stages are not available: with few exceptions, their somatic parts are very similar to each other. They have defined cell walls and are generally immotile, although they may have mobile reproductive cells, and they reproduce by means of spores. They obtain their food as parasites or as saprobes. Forming symbiotic relationships with algae or bacteria (or both), these fungi are able to feed off carbohydrates photosynthesized by their partners, so do not need moist environments to thrive (Alexopoulos, 1964).

Fungi range in size from tiny to huge. Microscopic yeast are fungi, as are *Armillaria ostoyae*, a dark honey fungus which are among the largest organisms in the world: recorded as extending across more than 10 km^2, a single genetic individual (Sheldrake, 2020).

Mycorrhizae are symbiotic associations between plant roots and fungi that expands beneath the ground creating a network of connection between plant species, something like the internet network, which allows them not only to communicate, but also care for, protect, feed and stock up on water, by exploiting a larger volume of soil than roots alone can do. Mycorrhizae come in a number of forms, dependent upon both host plant and fungal taxonomy (Van der Heijden *et al*., 2015). Mycorrhizae can be:

1) endomycorrhizas, characterized by inter-and intracellular fungal growth in root cortex, forming specific fungal structures, referred to as vesicles and arbuscules. This characteristic growth gives the endomycorrhiza the alternate name of vesicular arbuscular mycorrhiza. It is the most widely distributed association in plants. About 80% of all terrestrial plant species form this type of symbiosis and 95% of the world's present species of vascular plants belong to families that are characteristically mycorrhizal;
2) ectomycorrhizal fungi are also found in natural environments, mainly in forest ecosystems. These fungi can form visible reproductive structures (mushrooms) at the feet of trees they colonize. Ectomycorrhizal fungi grow between root cells without penetrating them. Their hyphae grow externally, forming dense growth known as a fungal mantle. These fungi form symbiotic relationships with most pines, spruces and some hardwood trees including beech, birch, oak and willow.

4.2 MUSHROOMS

The mushrooms are the umbrella-shaped fruiting body (sporophore) of certain fungi, typically of the order Agaricales, play an important role in their life cycle. Popularly, the term mushroom is used to identify the edible sporophores; while the term toadstool is often reserved for inedible or poisonous sporophores. There is, however, no scientific distinction between the two names, and either can be properly applied to any fleshy fungus fruiting structure

(E. Britannica). Mushroom's purpose is to create and disperse spores (the agents of asexual reproduction), microscopic, unicellular reproductive cells. A single mushroom can produce billions of spores a day. The spores may be released actively or passively. In the former the fungus, through its own actions, ejects the spores from the basidia or asci with considerable force. In the latter the fungus relies on some other agent to release the spores from the fruiting body. The agents are varied - wind, impact, water, insects. After the initial release, some other agency may be responsible for further dispersal of the spores. Most fungi disperse their spores by air, on animals or in water droplets. The spore-bearing structures are often ephemeral or appear seasonally (although fungi that form lichens have persistent spore-bearing structures) and the timing of fungal spore release dictates survival during atmospheric transport (Douhan *et al*., 2011; Golan and Pringle, 2017; Oneto *et al.* (2020).

For centuries, humans have appreciated edible mushrooms for their flavor and richness in protein (Pollan, 2006). Edible mushrooms are fleshy fruit bodies of several species of macrofungi. Edibility may be defined by criteria including the absence of poisonous effects on humans and desirable taste and aroma. There are around 3000 edible mushrooms in the fungi family. The most cultivated edible mushroom worldwide is *Agaricus bisporus* (common mushroom) followed by *Lentinus edodes* (shiitake mushroom), *Pleurotus spp*. (in particular oyster mushroom), and *Flammulina velutipes* (enoki mushroom). They are rich sources of nutrients including protein, amino acids, and dietary fibre, antioxidants, terpenoids, lectins, phenolic compounds, polysaccharides, and ergosterols.

Edible mushroom production and trade are expanding globally, as they can be safely dehydrated or freeze-dried. Fresh consumption is practically limited to local production due to short shelf life, as mushrooms typically last three days at ambient conditions and five to eight days in a cold storage system (Huo *et al*., 2023; Shonte *et al*., 2024). Portobello mushrooms are one of the most popular edible mushroom varieties and are often used as a meat substitute in vegetarian dishes. Also very appreciated: Shiitake, Morel, Chanterelle, Enoki, Maitake, Oyster and Cremini mushrooms.

Edible mycorrhizal fungi (EMF) include truffles (Périgord black truffle, Italian white truffle etc.) and other highly prized forest mushrooms (porcini, chanterelles, matsutake etc.). Most EMF truffle species belong to Ascomycota, while edible fungi belong to Basidiomycota.

Truffles are ectomycorrhizal fungi, so they are usually found in close association with tree roots. Spore dispersal is accomplished through fungivores, animals that eat fungi. These fungi have significant ecological roles in nutrient cycling and drought tolerance. To date, the vast majority of commercial EMF are sourced from natural, wild ecosystems. Truffle cultivation is very recent in human cropping history and additional research is needed to increase yields and profitability (Guerin-Laquette, 2021).

5 FUNGI IN AGRICULTURE SUSTAINABILITY

In nature, rhizospheric soils contain innumerable biological living beings to favor the plant development, nutrient assimilation, stress tolerance, disease deterrence, carbon seizing and others. These organisms include mycorrhizal fungi, bacteria (Radhakrishnan & Krishnasamy, 2024), actinomycetes, etc., which solubilize nutrients and assist the plants in uptake by roots and can act in the control of pests, weeds, and plant pathogens as an alternative to chemical pesticides.

Amongst the so-called beneficial fungi, that comprise mycorrhiza, endophytic fungi, entomopathogenic fungi, mushroom, and dark septate fungi (Al-Ani *et al.*, 2021), arbuscular mycorrhizal fungi (AMF) have key importance in natural ecosystem. The majority of the terrestrial plants form association with AMF, that are obligate biotrophs and ingest plant photosynthetic products and lipids to accomplish their life cycle. The symbiosis of AMF, a soil-borne fungus, with plants had been reported to date since 400 million years ago (Selosse et al., 2015). This symbiosis confers benefits directly to the host plant's growth and development through the acquisition of mineral nutrients from the soil by the AMF; also play a basic role in different physiological processes as well as mineral and water uptake, chemical change, stomatal movement, and biosynthesis of compounds termed biostimulants, auxins, lignan, and ethylene to enhance the flexibility of plants to ascertain and cope environmental stresses like drought, salinity, heat, cold, and significant metals. This is achieved by the growth of AMF mycelium within the host root (intra radical) and out into the soil (extra radical) beyond. Some show high efficiency in the reduction of plant diseases such as producing secondary metabolites and induced plant defenses and systemic resistance. It is believed that AMF improves the uptake of almost all essential nutrients and contrarily decreases the uptake of Na and Cl, leading to growth stimulation (Evelin *et al.*, 2018).

Numerous reports have shown that AMF have the potential to enhance plant growth under stressful environments as well as the potential of AMF application on aggregate stability in soils (Sun *et al*., 2018; Hashem *et al*., 20018; Liu *et al*., 2018; Syamsiyah *et al*, 2018; Begum *et al*., 2019; Li *et al.*, 2019; Abdelhameed and Rabab, 2019; Chandrasekaran *et al.*, 2019; Mitra *et al.*, 2019; Ait-El-Mokhtar *et al*., 2019; Santander *et al*., 2019; Wahab *et al.*, 2023; Jia *et al*., 2024).

Arbuscular mycorrhizal symbionts on plant growth and health have been reported for many species, and supports their use as biofertilizers and bioenhancers. Another example is the biofortification and accumulation of health-promoting compounds achieved by AMF. The higher Zn and Fe uptake by mycorrhizal plants was significantly correlated with higher carotenoid, inulin, and fructose levels, suggesting a relationship among the modulation of micronutrient uptake by mycorrhizal symbionts and the biosynthesis of health-promoting molecules by the host (Pepe *et al.*, 2022).

The adoption of bio-inoculants of AMF is an emerging soil fertility management practice with potential to increase and cheaply improve crop yields. Nevertheless, inoculum production and adoption in specific regions, such as sub-Saharan Africa smallholder systems, is still limited mainly by research capacity and technological challenges (Mukhongo et al., 2016). AMF are especially important for sustainable farming systems because they are efficient when nutrient availability is low and when nutrients are bound to organic matter and soil particles (Devi *et al*, 2021).

Another action of AMF that is worthy to mention is in bioremediation. Bioremediation is a term that defines biologically mediated processes during which an undesired compound is transformed, degraded, sequestered and/or entirely removed from the ecosystem. Organisms across all domains of life may mediate bioremediation; yet, fungi are particularly promising candidates. They possess metabolic capabilities to break down complex molecules which make fungi the ultimate degraders of recalcitrant organic matter in nature. Bioremediation by fungi, also termed mycoremediation, has been more frequently investigated in terrestrial than aquatic ecosystems, although fungi also thrive in lacustrine and marine environments. Some authors focused also on the safety aspects of mushroom cultivation on waste (Kulshreshtha et al., 2014; Yin *et al.*, 2016; Vaksmaa *et al*., 2023).

In several aspects, mycorrhizal fungi appear as key players in environmentally sustainable agriculture. Some authors extend that role as also a “saviour” for achieving food security (Thirkell *et al.*, 2017).

6 CONCLUSION

Environmentally and economically, agriculture has proven to be an important sector that plays a role as a main backbone in many economies of the world. At every stage/ aspect of agriculture, biotechnology has a vital role to play since one ultimate objective of agricultural biotechnology is the production of safe food and agro-based industrial raw materials for the ever-growing world population. The importance of fungi used in the fields encouraged to inter them in the industry to produce the biopesticides and biofertilizers which can be used in the place of synthetic chemicals reducing the residue of chemicals in the environment. Proper management of arbuscular mycorrhizal fungi (AMF) has the potential to improve the profitability and sustainability of agricultural systems. It is possible that the greatest benefit of high AMF colonisation in crop plants is non-nutritional, via the effects on soil structure and function, and on plant defences. As such, future work should focus on optimising AMF effects on nutrient uptake towards achieving food security in more sustainable agricultural systems.

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