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Positioning plant health within the evolving human-animal-environmental health paradigms

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ABSTRACT

The evolution of the global scenario, which involves such converging crises as the climate crisis, the COVID-19 pandemic and its aftermath, and the Russia-Ukraine and Israel-Palestine wars, has underscored the fragility of the current food systems and the interdependence of human, animal, plant, and environmental health. Plant health is an important element in all these crises as plants provide food and feed, fix CO_2, produce oxygen, and stabilize the soil. As a result of the Covid 19 pandemic, the One Health concept has finally obtained the attention of scientists and funding agencies. However, despite their role in global nutrition, the economy, and in climate crisis, plants are often excluded from the One Health efforts and funding streams. This paper advocates the need for an updated and more holistic view of plant health as public goods within the context of the evolving global challenges and explores opportunities within the Circular Health paradigm.

1. Plant health and its impact on human health (Fig. 1)

1.1. The climate crisis, the COVID-19 pandemic and the ongoing conflicts as turning points

The past few years have seen several disruptive episodes, and these have brought many novel issues to the attention of the public and policymakers that cannot be ignored. The disruption caused by COVID-19 made a concept that had already been suggested very clear [1]: the threat to food security during a health crisis is unavoidable [2]. Moreover, during the COVID-19 pandemic, the importance of environmental health, with plants as a key component, became evident. The ongoing climate crisis is severely challenging future food production by influencing pathogen evolution, altering host–pathogen interactions, and contributing to the emergence of new pathogenic strains. As a result, the geographical range of pathogens may expand, leading to the spread of plant diseases in new regions [3]. Moreover, climatic changes are determinants of the fitness of crops in rising temperatures and can lead to changes in crop productivity and/or crop diversity in agricultural production areas [4]. Additional international crises, such as the Russia-Ukraine war, is reminding all of us how fragile our agricultural production systems are [5]. Indeed, war affects food production as a result of soil degradation and pollution. Plant health is deteriorating because of the increasing persistence of pathogens as well as the decreasing chemical and physical properties essential for the proper development of plants [5,6]. It is now even clearer that animal and human health are closely connected to the health of the environment and plants. All these sectors share common challenges, such as antimicrobial resistance, which is known to occur in agriculture, and in veterinary and human medicine. Another cross-cutting topic that affects global health is the presence of mycotoxins in food, feeds, and in agriculture, and this can only be effectively tackled through a farm-to-fork approach [7].

1.2. The role of plant health in food security

Food security crises, which were mostly related to developing countries for many years, are now considered possible in industrialized countries, because of the climate crisis and wars. An increased crop productivity is essential for long-term food security, especially with a growing global population. The food security challenge is quite complex, as it requires focusing on the health of both humans and the planet [8]. Furthermore, potential solutions to improve food security should also address equal distribution of food, thus avoiding increasing poverty. Among the factors that can impact crop productivity (soil fertility,

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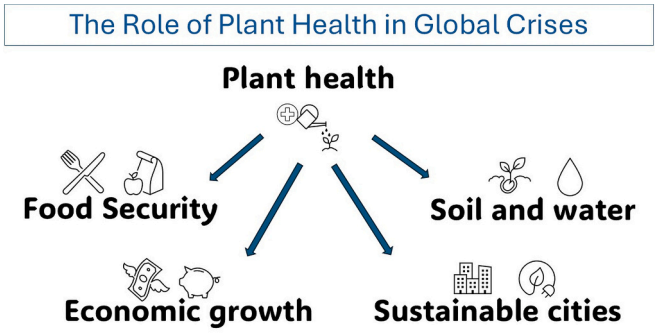

Fig. 1. Plant health and its impact on human health

fertilizers, soil degradation, drought, water management, credit access…), pre-and post-harvest losses due to pests are significant, ranging from 25 to over 50 %, with differences among crops and geographical areas, as clearly documented in accurate surveys that were carried out at different times [9–12]. Furthermore, the COVID-19 pandemic had impacts on crop protection, increasing crop losses and, consequently, reducing yields [13]. Consequently, one very important aspect of food security is minimizing losses both during cultivation and after harvest [14]. The availability of seedlings and planting materials in some countries was reduced by the recent pandemic, having impacts on agriculture and food systems [15]. The use of healthy vegetative planting material is crucial, not only for a sustainable crop productivity but also for human food security [16], as shown, for instance, in the case of yam (*Dioscorea rotundata*) in Nigeria [17] and banana in several countries worldwide [18]. Despite the knowledge of its relevance to food security, plant health has been considered as a minor player in the global health approach, compared to animal and human health. Unfortunately, the past few decades have been characterized by less funding for research and less attention to the importance of plant health, despite the growing interest in the issue of food insecurity. For example, the yearly Union co-financing rate for phytosanitary and veterinary programmes and emergency measures has been reduced by 60 % for the period from 2023 to 2027, as a consequence of the budget previously allocated to such programmes being reallocated to tackle unforeseen sanitary crises [19].

1.3. The role of plant health in economic growth

The United Nations (UN) projects that the world's population will surpass 9 billion people by 2050, with most of this increase in low- and medium-income countries. The Food and Agriculture Organization (FAO) estimated that 811 million people were undernourished in 2020, partly due to the impacts of the Covid-19 pandemic [20]. To achieve the UN's second Sustainable Development Goal, agricultural production must rapidly increase, particularly in the southern part of the world, even as challenges such as water scarcity, climate change and losses due to pests persist. Ensuring plant health will contribute significantly to food security, safety and economic growth, in both industrialized and emerging countries [21–24].

1.4. The role of plant health in sustainable cities

Plant health plays a crucial role in sustainable cities. By promoting plant health in urban areas, it is possible to help create more sustainable and healthier cities. This can involve designing more green spaces, promoting urban agriculture, using an integrated pest management system, and designing function-specific plant systems. Such actions help to reduce the urban heat island effect, improve air quality, and promote biodiversity, thus making cities more sustainable and healthier [25,26]. Plant pathogens, including viruses, bacteria, and fungi, can be transmitted from ornamental plants in parks and gardens to agricultural crops [27], thus requiring attention on the monitoring and control of plant health problems in cities to avoid they can reduce yields and food security. Furthermore, cross-kingdom pathogenic microorganisms, including certain bacteria and fungi, have been documented to cause diseases across a variety of hosts, including plants, animals, and humans [28]. For instance, *Aspergillus fumigatus* can thrive in diverse environments, including gardens and potting mixtures in the cities, posing risks to both plant health, pets and human well-being [29]. Plant diseases also influence land use and environmental regulations in general, and they require interdisciplinary research and stakeholder involvement [30]. However, the microbial biodiversity of plants is different in public gardens and urban forests, and this suggests that native plant species should be given more emphasis in gardens [31]. Arboreta and botanical gardens can provide key resources to support urban forestry efforts, and the involvement of botanical gardens in urban forestry can, consequently, improve the sustainability of cities and address challenges related to climate change [32].

1.5. Impact on soil and water

The health of plants has an important impact on the quality of soil (earth), water, and air, which, in turn, directly impacts plant health. Understanding these interconnections is essential to obtain sustainable agriculture and ecosystem health. Healthy plants contribute to soil health in various ways. Their root systems stabilize the soil, prevent erosion, and promote the soil structure. Furthermore, plants add organic matter to the soil through decaying plant material and root exudates, thereby enhancing soil fertility [33].

A thriving plant community influences the soil microbiota, which plays a crucial role in nutrient cycling and disease suppression [33]. Healthy plants also support a diverse microbiome, contributing to the overall health of the ecosystem [34]. Plants are crucial in preserving both the quality and availability of water. They store and filter water, reduce the risk of contamination and ensure a sustainable supply of clean water. Plants in riparian zones along water bodies help mitigate the impact of pollution by filtering out contaminants, stabilizing the soil, and reducing erosion and sedimentation [35].

The complex interplay between plants, soil, and water highlights the importance of a holistic approach to the management of plant health. Adopting sustainable agricultural practices that focus on enhancing soil health, safeguarding water resources, and reducing chemical inputs essential for maintaining the Circular Health of ecosystems.

2. From plant pathology to plant health towards a complete circular vision

2.1. The evolution of the One Health concept: an ever-expanding vision, not just a matter of definitions

It is now recognized that agriculture and food systems are crucial in the global agenda for nutrition and health, as they allow shared solutions to be implemented with the other sectors, and the challenge of improving nutrition and health to be confronted, thereby ending, or at least reducing hunger, while protecting the environment [36]. In this context, many efforts have addressed the importance of integrating disciplines and approaches when considering health.

Here, we briefly analyse the history of the One Health concept and how the Circular Health paradigm can lead to a more effective and comprehensive approach to tackle health issues, and we also show how plant health should be included among the cardinal sciences that lead the efforts to achieve the health of the whole planet.

2.2. Veterinary science and medicine: a historical perspective and the concept of one medicine

Global health started to become popular two decades ago [37]. The definition of global health then included human and animal health, and many existing relationships were recognized as well as the possibility of developing and sharing a variety of techniques and methodologies. However, despite the recognition of the need for greater collaboration, it has often been difficult to build a solid partnership between the plant health and human/animal health communities. There are diverse reasons for this; it has sometimes been due to the different methodological approaches that are adopted, but also to the need to overcome the traditional barriers that exist among disciplines, as well as to strong competition in the accession to research funds and a very conservative attitude of the disciplines to protect themselves.

In the past few decades, research into infectious diseases affecting humans and animals has faced increasingly complex challenges. Factors such as the increase in the human population, the rapid urbanization that is occurring in many developing countries, intensified livestock production, pollution, environmental degradation, and globalization need an integrated approach to be dealt with. Such an approach is not new, since ancient healers often cared for both animals and humans [38]. Moreover, often being priests, they also took care of souls. During the Zhou dynasty in China, in the 11-13th centuries, one of the earliest integrated public health systems was established, incorporating both veterinarians and medical doctors [39]. In France, Claude Bourgelat, who founded the first veterinary school in Lyon in 1762, introduced human clinical training into the veterinary *curriculum* [39].

William Osler, who introduced the concept of "one medicine" to North America, emphasized the integration of medical thinking across disciplines [40]. However, by the 20th Century, the fields of medicine and veterinary medicine had become so specialized that opportunities for collaboration diminished. In 1976, Schwabe revitalized the concept of "one medicine", acknowledging the close interaction of animals and humans for livelihood, nutrition, and health [38]. Today's understanding of "one medicine" draws from practical experiences in African communities, where the same person often provide care for both animals and humans.

Indeed, human and veterinary medicine share a unified paradigm, with both sciences drawing on a common body of knowledge in disciplines such as physiology, anatomy, pathology, and epidemiology. Many cancer-related genes were first identified in animals before similar diseases were recognized in humans [1]. The significant contributions of veterinary medicine to public health have been fully recognized by major international organizations, including the Food Agriculture Organization (FAO), the World Health Organization (WHO), and the World Organization for Animal Health (OIE), which oversee and address these critical issues [41].

2.3. Evolutions of the One Health concept

The term "One Medicine" [1] has a rather clinical connotation and does not fully reflect the variety of interactions that take place between human and animal health. Such interactions include ecology, public health, as well as other aspects such as anthropology, behavioural sciences, and adaptation mechanisms. "One medicine" evolved into "One Health" through a modern understanding of health and ecosystems, and to significance for global public and animal health. The term "One world, One health", which is trademarked, was first introduced during an expert consultation in Winnipeg (Canada) in 2009 [1]. This term emphasizes the need to address the risks of infectious diseases at animal-human-ecosystem interfaces [1]. Over the past 20 years, the "One Health" concept has significantly advanced, leading to increased awareness, scientific discussion, research initiatives, and practical applications in epidemiological studies, disease surveillance, and healthcare [1]. Several zoonoses have demonstrated the benefits of adopting a broader perspective [42]. However, despite the clear advantages of "One Health" over traditional sector-specific approaches, the real efforts of collaboration between animal and human health sectors have often remained fragmented. This is particularly true in Europe, where even the most advanced research programs tend to maintain separate funding streams for animal and human health, notwithstanding the etiological link. For example, 29 projects exclusively focused on influenza for a total value of 41.7 million € were funded under the Sixth Framework (2002–2006). This probably happened in some cases just because of a very conservative attitude to maintaining the funding separated, with a strong and negative fragmentation of veterinary and medical science into subdisciplines [43]. On the other hand, several episodes provide evidence of public health benefits through joint disease surveillance, thereby fostering interactions between animal and human health at academic institutions, government ministries, and international organizations [44]. The increasing frequency and severity of health threats that impact the animals, humans, plants, and the environment over the past decade have renewed attention to the "One Health" concept. Consequently, the United Nations has developed a One Health Joint Plan of Action [45]. In 2018, the One Health Commission (2018) defined "One Health" as "the collaborative effort of multiple health science professions, together with their related disciplines and institutions, working locally, nationally, and globally to attain optimal health for people, domestic animals, wildlife, plants, and our environment" (One Health Commission). Various alternative definitions have been formulated [41,46–48] to include a wide range of dimensions in the definition.

2.4. Planetary Health

In an attempt to expand the integration of multiple disciplines, the term "Planetary Health" has emerged to address the complex challenges associated with the Anthropocene, a new geological era marked by significant human impact on Earth's biophysical systems. While the overall health of the global population has improved in the past century, the stability of the planet's life-support systems has sharply deteriorated, putting public health and development gains at risk. In addition to climate change, global pollution of soil, water, and air; shortages of arable land and freshwater; alterations in land use and cover; and degradation of marine ecosystems all threaten the health of our planet.

"Planetary Health" is a solution-oriented, interdisciplinary field and social movement dedicated to analyzing and addressing the effects of human disruptions on Earth's natural systems and their impact on human health and all forms of life [49]. "Planetary Health" is a new science that involves exceptional actions and a global movement. It first emerged as a discipline in 2014 [50]. "Planetary Health" is defined as the health of human civilization and the natural systems upon which it relies. In this broad definition of health, plant health is not only recognized, but it has also become a cornerstone topic. Anthropogenic environmental changes impact water and air quality, food availability and safety, exposure of plants, animals, and humans to infectious diseases, and even the habitability of various regions. Plant health is essential for advancing planetary health by contributing to sustainable and healthy urban environments [51]. For instance, plants can help reduce greenhouse gas emissions from fossil fuels, improving air quality by mitigating fine particulate pollution, and enhance urban resilience to climate change [52,53]. Green spaces within cities can reduce the urban heat island effect, support biodiversity, and benefit mental health [54–56]. Watershed conservation efforts can ensure a clean water supply for urban areas while mitigating biodiversity loss, flooding, and soil erosion. Additionally, improving slums and informal housing can decrease vulnerability to disasters and extreme temperatures, increase access to clean household energy, and help alleviate poverty [57].

Reducing food waste is another significant policy for enhancing planetary health [58]. Approximately 30 % of global agricultural land is used to produce food that ultimately goes uneaten. Addressing this issue requires improvements in harvesting, storage, transportation,

marketing, and consumption practices [59]. Additionally, many crops are diverted from direct human consumption to feed animals, driven by rising demand for animal products. The inefficiencies in converting feed to animal products vary, with beef showing particularly high inefficiencies. Animal products, especially those from ruminants, tend to have a higher greenhouse gas emissions compared to vegetables due to methane production during digestion. Although, it has to be underlined that without ruminants consuming forages, probably a lot of marginal agricultural land would not be used for food production. Shifting towards greater consumption of fruits and vegetables while reducing animal product intake in high-consuming populations can reduce environmental impacts and promote better health [60,61]. This area presents an important opportunity for future research, requiring collaboration across disciplines such as agricultural, health, and environmental science to address these interconnected challenges effectively.

2.5. Circular Health

Circular Health is a new paradigm concerning the advancement of health as a system. It is rooted in the One Health and Planetary health principles but aspires to be more inclusive and contemporary. It recognizes big data as a source of innovation and considers non-biomedical disciplines essential for the advancement of health as a system [62]. In addition, the Circular Health paradigm has a close link with the SDG roadmap, which can serve as an implementation tool [63]. The close link with the SDG roadmap represents an opportunity for plant health to become a key player in the development of the Circular Health paradigm.

The Circular Health approach also emphasizes that the health of animals, plants, and humans is intrinsically linked to the delicate balance between the living and inanimate forces of earth, air, water and fire, and that man-driven interventions in one area can have ripple effects throughout the ecosystem [62,64].

2.6. Plant health and Circular Health

In recent years, the role of plant health has been recognized more and more in the One Health and Planetary health communities that acknowledge the critical role that healthy plants play in sustaining ecosystems and supporting human well-being [65]. Despite this, we believe that, within the Circular Health paradigm, plant health can drive the efforts to improve health at a global scale by incorporating the essential component of the Circular Health paradigm, which emphasizes a regenerative and holistic approach to health. Circular Health underscores the interconnectedness of various health domains and advocates the sustainable use of resources and the reduction of waste. Circular -Health principles can be applied, in the context of plant health, to achieve a more sustainable and resilient agricultural system [66] and provide linkages with the concept of Circular agriculture, which is aimed at minimizing waste, reducing environmental impacts, and promoting resource efficiency. Indeed, plant health is pivotal in this paradigm, as healthy crops are more resilient to diseases, pests, and environmental stressors, thereby reducing the need for chemical interventions. Promoting plant health through sustainable farming practices, such as crop rotation, through organic farming, and integrated pest management, aligns with the Circular Health principles by reducing the ecological footprint of agriculture [66,67].

The Circular Health framework also recognizes the reciprocal relationships between the environment and plants. Healthy plants play a crucial role in enhancing environmental quality and maintaining the balance of an ecosystem. As plants photosynthesize, they absorb carbon dioxide from the atmosphere and release oxygen, which is essential for animal and human health. Healthy plant populations help maintain the soil structure, prevent erosion, and sequester carbon, thus contributing to a sustainable and resilient environment. Additionally, plants filter and store water, thereby contributing to the availability and quality of water. Preserving and maintaining biodiversity is also a key element of Circular Health [62]. A diverse plant community enhances ecosystem resilience by providing a buffer against environmental disturbances [68].

2.7. The influence of external drivers (Fig. 2)

Plant health within a Circular Health framework is influenced by a multitude of external drivers that can result in both indirect and direct impacts on the health of animals, plants, and humans. Those drivers may not significantly affect plant health more than human and animal health, but understanding these drivers is crucial to develop effective strategies that can be used to protect and promote plant health [24,68].

Climate change is a major external driver affecting plant health. Rising temperatures, shifting precipitation patterns, and more frequent extreme weather events create conditions that favor the spread of plant diseases and pests [69,70]. Plant pathogens, including fungi and bacteria, may expand their geographic range due to the emergence of new disease vectors. To mitigate the adverse effects of climate change on plant health, it is crucial to implement adaptive strategies [70]. These should encompass empowering farmers to develop crop varieties resilient to changing climates, enhancing irrigation and water management practices, and improving disease surveillance and early warning systems [69].

The mechanisms of globalization and the rapid movement of people and goods across the planet have increased the risk of introducing plant pathogens to new regions [71]. This can result in the spread of diseases that were once restricted to specific areas. Quarantine measures, strict phytosanitary regulations, and international cooperation are essential to prevent the unintentional introduction of harmful pathogens. The globalization of trade can also facilitate the emergence of new diseases as pathogens interact with plant species they have not encountered before. This creates challenges for the management of plant health and requires constant vigilance through monitoring and surveillance [69].

Land use changes, such as deforestation, urbanization, and agricultural expansion, can disrupt natural ecosystems and have profound consequences on plant health [72]. Fragmentation of habitats can lead to increased contact between livestock, wildlife, and crops, thereby increasing the risk of disease transmission. Adopting sustainable land management practices, such as reforestation, maintaining green corridors, and protecting natural habitats, can help mitigate the adverse effects of land use changes on plant health and preserve biodiversity [72,73].

2.8. The need for multidisciplinary collaboration

The complexity of plant health within the Circular Health framework necessitates multidisciplinary collaboration [24,64,68] and a greater

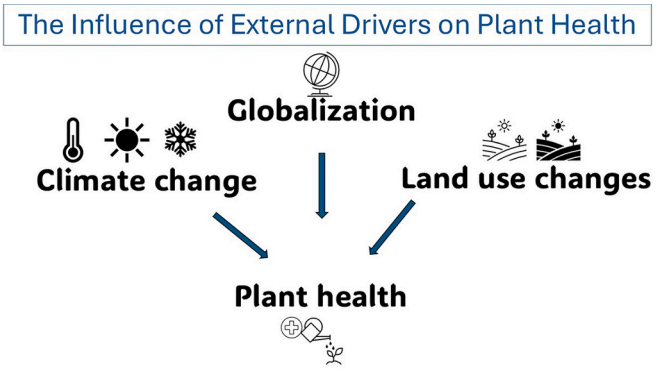

Fig. 2. Plant health within a Circular Health framework: the influnce of external drivers.

permeability of disciplines. Indeed, to effectively address plant health issues, it is essential for researchers, policymakers, and stakeholders from various fields to collaborate synergistically.

To achieve an effective plant health, it is important also to recognize the role of "Medicine of Plants" or "Phytiatry", which is applied only in a few countries, as a distinct multidisciplinary science like Medicine and Veterinary Medicine and established as an indispensable part of a global health concept [74]. Qualified specialists able to work as Phytiatry (plant medicine) doctors are consequently needed world-wide [75].

Collaboration between plant pathologists, phytiatry doctors, veterinarians, public health officials, ecologists, and social scientists is crucial to develop holistic strategies that promote plant health and prevent disease transmission [64]. Multidisciplinary teams can improve the early detection and surveillance of emerging plant diseases that may have a zoonotic potential. Identifying and monitoring these diseases at their source is crucial for preventing outbreaks in humans and animals [24].

The efficient sharing of information and data integration are vital components of multidisciplinary collaboration [76]. The development of shared databases, information systems, and research networks can facilitate the exchange of knowledge and expertise among different stakeholders. Establishing centres and/or institutes with a circular vision, which involves bringing experts from various fields together, can serve as a hub for collaboration and research [77]. These centres can foster innovation and the development of interdisciplinary solutions to deal with plant health challenges. Multidisciplinary collaboration should also extend to policy and decision-making. Governments, international organizations, and local communities should collaborate to develop and implement policies that address plant health issues. This collaboration can lead to more effective regulations, better resource allocation, and enhanced public awareness campaigns [78].

3. Conclusions

Plant health should be part of the Circular Health vision and can significantly contribute to its advancement. Such a vision encompasses and advances the One Health concept. It is important to acknowledge that the One Health approach to managing plant diseases is still in its early stages [79] and has only been tried in a few cases, but there is strong evidence that coping with them through a more comprehensive vision will be more successful and cost-effective. However, it is important to avoid just a limited interpretation of this approach to ensure the development of effective and comprehensive collaboration across sectors and disciplines. A recent systematic analysis of One Health networks indicates that most were established after 2005 and that many do not include the private sector [80]. Such an approach will be helpful not only for researchers but also for the many professionals that act in different fields (i.e. nature conservation, extension services, plant doctors, veterinarians, medical doctors) as it provides them with new tools to function with a more holistic view. In other words, for many years, traditional educational approaches were taught in isolation and separately, which often inhibited collaboration. The new challenge is to develop interprofessional education to prepare better professionals for the future. COVID-19 has been an accelerator of interdisciplinarity, that is, a unique opportunity to change. Convergence, interdisciplinarity, and a novel circular approach focused on advancing the health of animals, humans, plants, and the environment will contribute to redesign a healthier and more resilient ecosystem [81]. This approach aims to create systems that are less vulnerable to disruptions and more sustainable [81]. Plant pathology, with its emphasis on plant health, food security, and environmental challenges [78], after having been erroneously neglected for years, can now play an important role in the frame of Circular Health. The new tools provided by big data and artificial intelligence should help the implementation of optimal multi-sectorial collaboration in surveillance systems, which will be helpful for the involved organizations [82].

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CRediT authorship contribution statement

Maria Lodovica Gullino: Writing – review & editing, Writing – original draft, Conceptualization. **Matias Pasquali:** Writing – review & editing, Writing – original draft, Conceptualization. **Massimo Pugliese:** Writing – review & editing, Writing – original draft, Conceptualization. **Ilaria Capua:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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