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Where is the plant-space research going? An overview on the last two decades through bibliometric network multi-analysis

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ABSTRACT

In recent decades, the interest of the scientific community in plant space biology increased based on the certainty that cultivating higher plants in space is imperative for prolonged human missions. The cultivation of plants in space assumes great relevance moved by the consideration that there is a pivotal need to improve resource regeneration and onboard production of plant-based food, thus reducing the supply of resources from Earth. Therefore, the hereby paper provides an overview on the evolution of the interest in plant space biology from 2000 to 2023, basing the search on specific keyword combinations. The study encompasses (i) a proper quantitative search on the Scopus database; (ii) keyword frequencies and clustering analysis, (iii) a keyword network and time-gradient analysis and (iv) an elaboration of knowledge gaps comparing our results and recent reviews. Results highlighted an increase in publications in the last 10 years and a specific time-gradient related shifting on subtopics such as *in situ* resource utilization (ISRU) application and food production in a space mission context. Currently, knowledge gaps were identified in four research areas related to water dynamics in extra-terrestrial environments, plant physiology and biochemistry in response to growth on regolith, interactions with fertilizers, and plant/soil microbiome. Identifying these gaps will allow to canalize future efforts of space research where needed, facing the unsolved questions. Our analysis pointed out that space plant biology turned out to be oriented towards short and long-term space mission applications for improving resource regeneration and onboard/extraterrestrial-grounded production of plant-based food, thereby diminishing reliance on Earth for resupply.

1. Introduction

In the early stages of space exploration, the emphasis of life science research was mainly devoted to studying the human body and developing a pivotal understanding of its reactions to the challenging space environment. The aim was to mitigate health risks and safeguard astronauts by addressing space-induced health issues during space travels and long-term space missions [1,2].

The interest in space biology and exploration into various facets of life on celestial bodies has reinforced the challenge of extraterrestrial exploration and promoted multidisciplinary studies to cover different, important issues related to space research. These studies encompass diverse subjects, including the impact of gravitational variations on celestial bodies compared to Earth [3], space factor effects on living organisms [4–6], the efficient recycling of oxygen and water [7], and sustainable food production within controlled environments or bioregenerative life support systems (BLSS) [8].

Over the past few decades, a rising interest was observed in plant space biology. This shift is driven by the recognition that cultivating plants in space, especially crops valuable to provide astronaut' diet with fresh food, is crucial for extended human missions. The present aspect is essential considering that the resource regeneration and on-board production of plant-based food will help reduce the dependence on Earth for resupply [9]. Recent scientific innovations and technological progress hold the potential to facilitate space exploration and, in the distant future, enable the establishment of BLSS on celestial bodies beyond Earth [10]. Viewed through this lens, the prospect of exploring the Moon or Mars appears more achievable and imminent than merely belonging to the realm of science fiction.

Plants play a pivotal role in Bioregenerative Life Support Systems (BLSS). These advanced ecosystems, exemplified by BLSS, incorporate cutting-edge technology by integrating physico-chemical and biological

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processes to sustain extended interplanetary missions [11–13]. The BLSS framework comprises interconnected compartments utilizing various organisms for the sequential recycling of resources [14,15]. Existing food production systems in space are currently confined to modified hydroponic setups in microgravity, exemplified by systems like the Veggie growth system or the Advanced Plant Habitat aboard the International Space Station (ISS) [16]. Instead, an example of a BLSS is the MELiSSA (Micro-Ecological Life Support System Alternative) loop developed by the European Space Agency (ESA) [15]. These facilities are designed to reduce the initial payload and decrease dependency on Earth to sustain astronaut life during space missions [17].

Relying on terrestrial resources for permanent extraterrestrial human settlements is estimated to be economically unsustainable [18, 19]. An effective BLSS must guarantee water purification, atmosphere revitalization, and food generation within a closed-loop system [15,16]. Achieving this goal may also involve *in situ* resource utilization (ISRU), where native materials [20] and wastes serve as primary resources [21]. Instead of relying solely on a closed loop, incorporating new materials discovered on-site could render life support systems sustainable and expandable [8].

Implementing ISRU strategies to produce fresh food is not just a choice but a necessity to ensure sustainability in extraterrestrial BLSS. Utilizing the local regolith as a "soil" medium for plant growth emerges as a viable approach, although the characteristics of "extra-terrestrial soil" markedly differ from the vital and fertile "terrestrial soil" [22,23]. The sole regolith lacks organic matter or a microbiome. Many published studies testing the suitability of regolith for plant growth have used regolith contaminated with microbiomes [8,24].

Recently, significant transcriptional changes in *Arabidopsis thaliana* (L.) Heynh. were reported when grown on various Lunar regolith samples [25]. The findings revealed that while germination occurred for all seeds across different substrates, plants grown on real Lunar regolith exhibited stunted roots compared to those on the simulant. From a transcriptional perspective, genes associated with stress response, including salt, metal, and reactive oxygen species (ROS) stresses, were upregulated [25]. While earlier studies indicated the feasibility of plant growth on Martian regolith simulants due to the presence of essential nutrients [26], the absence of reactive nitrogen and the presence of perchlorate are identified as major limitations affecting plant growth on Mars [26].

Studies have shown that reactive nitrogen can be provided through the combination of regolith simulants and organic material. Researchers investigated the cultivation of different plants, such as tomato, rye, quinoa, pea, and radish, using Martian regolith simulants mixed with cut shoot tissues of ray grass as an organic nutrient source [26]. The presence of organic matter promoted germination and growth in all the examined plant species. Recently, the feasibility of utilizing alfalfa biomass to enhance basaltic regolith simulants, mimicking the actual Martian terrain, was demonstrated [27]. However, studies focusing on plant cultivation on Mars have employed varying ratios of simulants to compost or other amendments to improve the physicochemical and hydraulic properties of the Martian soil simulant [26,28–31].

An intriguing new aspect regarding space-simulant substrates for plant cultivation is the employment of plant growth-promoting bacteria (PGPB). These microorganisms offer various functions for host plants, usually in exchange for a range of carbon sources in root exudates [32]. Bacteria capable to scavenge nutrients from regolith or enhance nutrient uptake from fertilizers could significantly reduce the need for nutrients to be supplied from Earth. PGPB play a crucial role in making nutrients available for plants, reducing the reliance on external nutrient sources for growth [33,34]. In the interest of crew protection, all items dispatched to space, including seeds, undergo sterilization or sanitization procedures [35]. For instance, the ISS microbiome derived from human microbiome and provided to plants through watering, pruning, and harvesting activities [36], except for seed-borne endophytic microbes, would be unaffected by surface sterilization [37]. The potentiality of PGPB's application from an outer space mission perspective seems to be an uninvestigated field [32].

In this paper, our aim was to present a comprehensive overview of the evolving interest in plant application in a space context. We conducted a quantitative literature search detailing the distribution of publications by country, keywords (and their combinations) and years in the timeframe 2000–2023. Following this initial analysis, we delved into further research to explore the sub-topics co-occurring with the plant-space research field, and provide a quantitative literature search analysis implementing the study with cluster elaboration based on keywords co-occurrences. Finally, we proposed a comparative elaboration between our results and topic knowledge gaps.

2. Materials and methods

2.1. Data collection

In order to investigate on the mentioned topic, we built six text *corpora* based on five different queries over the Scopus database. We limited our searches to the areas of "Agricultural and Biological Sciences" (AGRI), "Biochemistry, Genetics and Molecular Biology" (BIOC), "Earth and Planetary Sciences" (EART), "Environmental Science" (ENVI), "Immunology and Microbiology" (IMMU) and "Physics and Astronomy" (PHYS) in the date range 2000–2023 (included), excluding non-English papers, reviews, surveys, notes and letters. The searches were conducted at the end of December 2023.

The explored keywords combinations were "Plant" AND "Extraterrestrial" (PE); "Plant" AND "Mars" (PMa); "Plant" AND "Moon" (PMo); "Plant" AND "BLSS" (PB); "Plant" AND "Astrobiology" (PA); and "Plant" AND "ISRU" (PI). We excluded the keyword combinations "Plant" AND "Space" and "Plant" AND "Outer" AND "Space" because of the overlapping occurrence of the word "Space" in actual extraterrestrial context and in other generic research fields. Bodies of 210 (PE), 748 (PMa), 562 (PMo), 104 (PB), 100 (PA) and 84 (PI) publications were gathered for bibliometric analyses.

We limited our approach to keywords, abstracts, and titles, aiming to minimize biases during text analysis, possibly caused by not-strictly related words, repetitions, words' similarity due to endings, conjugations and declensions. The outlined approach builds upon previous text mining analyses reported on Hay Mele et al. [38] and D'Alelio et al. [39].

2.2. RStudio analysis on keywords frequencies and clustering

Our analyses were carried out with the software RStudio v. 2023.06.1 + 524, in accordance with the PRISMA guidelines [40]. Search results were downloaded as two columns (keywords, DOI) csv file. The dataset was then imported in RStudio and filtered using the *tidyverse* package collection to eliminate inconsistencies like non-accessible, non-readable or uninformative publications. We used the cleaned dataset to investigate keywords' frequencies and clustering [39]. Tidied data frames were reduced to 35, 99, 56, 34, 14 and 5 publications for PE, PMa, PMo, PB, PA and PI, respectively.

The data frames were used as to build a Document-term matrix (DTM) single words and one with bigrams. The matrix represents an input for a term-frequency inverse-document frequency analysis (TF-IDF) using the *textmineR* package. The term frequency (TF) is the term occurrence in the DTM and the inverse document frequency (IDF) is the commonness or rarity of a term across the corpus. The IDF was calculated for all corpora except PI as

$$IDF = log_{10}\frac{N}{N_t}$$

where N is the total number of documents and N_t is the number of documents where the *t* term appears. PI exclusion was motivated by its small size.

Additionally, we examined documents clustering by term-based distance through cosine similarity calculated over TF-IDF vectors for both single words and bigrams. We first calculated the cos() values, then transformed these into distances, and subsequently applied hierarchical clustering using Ward's method as the merging rule. The dendrogram was cut to form 10 distinct clusters. Clusters reporting and repeating the keywords used for the searches were excluded from the analyses.

2.3. VOSviewer analysis on keywords networking and occurrences

We performed networking, occurrences counting and clustering elaboration on six corpora through the software VOSviewer (version 1.6.19) [41]. Network maps were elaborated displaying items according to their relatedness degree. The keywords co-occurrence networks were based on the publications number in which author keywords occur between two documents [41]. We set a minimum threshold of 5 occurrences for all the search results bodies, and clustering resolution of 1. The outcome for each search is represented by two maps with the same topology but different color schemes. One highlights the co-occurrences-based links between keywords, using colors to separate clusters, and the other one represents the network map based on the keywords' occurrence in their average publication year through a color gradient from blue (oldest publications) to yellow (newest publications). The time range is automatically elaborated by the software to highlight the major changes in paper publications' areas. Non-topic related keywords were manually removed and redundant keywords were merged.

3. Results

Bodies of 210 (PE), 748 (PMa), 562 (PMo), 104 (PB), 100 (PA) and 84 (PI) publications were gathered in the timeframe 2000–2023 (included) from the Scopus search. Bibliometric analysis was performed on three levels, recovering the dataset from the Scopus search results, and then, employing RStudio and VOSviewer softwares.

Fig. 1 displays the Scopus search results by the overmentioned keywords combination through the time period 2000–2023. Specifically, Fig. 1a shows the number of published papers *per* year, indicating a general uprising of the absolute number of publications in the last 10 years for the combination PMa (orange line) and PMo (grey line). However, normalization on the baseline of publications in the reported subject areas, mentioned in Materials and Methods, provides a more realistic overview on the publishing trend (Fig. 1b). Specifically, PMa combination ranges between 0.0011 % and 0.0056 %, showing a slightly increasing trend in the period 2009–2011. On the other hand, PMo combination constantly up-rises over the 2010–2011 timeframe. In both keyword combinations, we observed a decreasing trend in the time period 2008–2011 probably related to the empty timeframe of NASA Mars missions, that affected then the literature production on the topic. The other keyword combinations (except for PE) ranges between 0 and 0.0013 %, with an average of 4 publications *per* year. Since the PE combination encompassed a broader and more general bodies of publications, we observed a slightly higher number of published papers compared to PB, PA and PI. Fig. 1c reports twenty-one countries plus Europe *per* published papers separated by keyword combination, suggesting an enhanced focus on PMa, followed by PMo and PE. Europe has been inserted merging France, Germany, Italy, United Kingdom, Belgium and Spain published papers. These countries have been chosen because they represent those funding ESA more than 4.5 % of the total contributions as stated in ESA funding report [42]. Specifically, the United States reported a PMa > PMo > PE trend analogue to Europe's. They differed only for PA, PB, and PI, which were higher in Europe. PB was notably lower in the US. China and India reported over 50 values for PMa, followed by PMo.

RStudio analysis allowed us to retrieve keywords frequencies and clustering, operating in agreement with Hay-Mele et al. [38] and

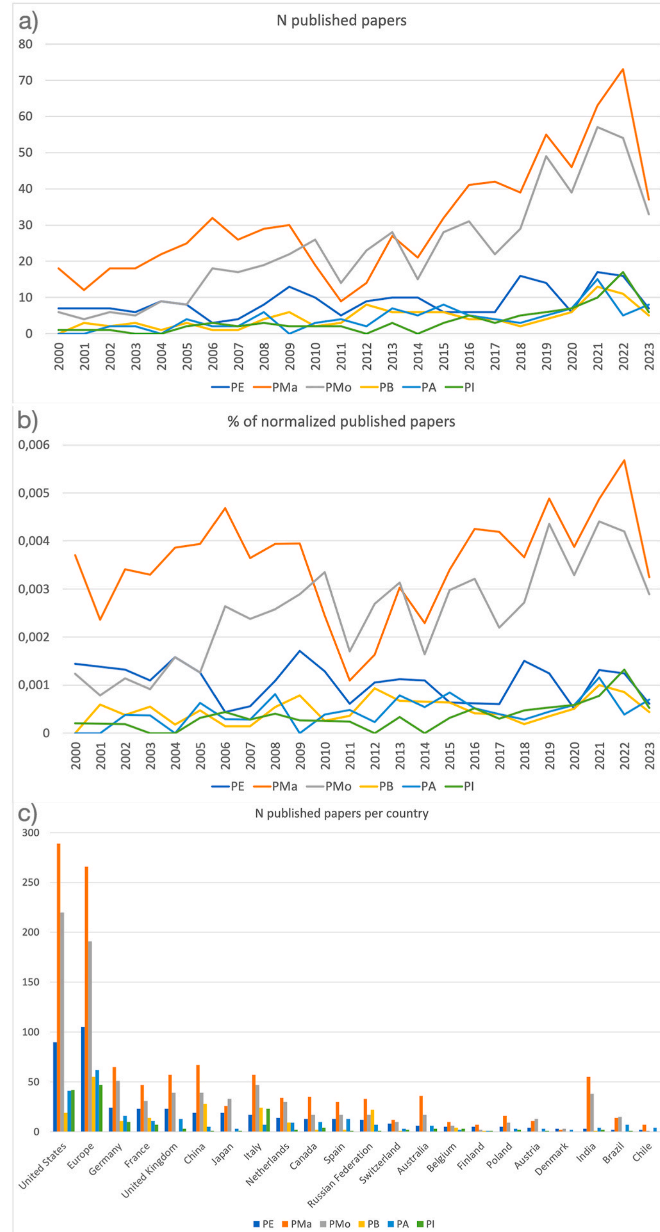

Fig. 1. a) Number of published papers *per* year in the timeframe 2000–2023 (till December 2023). **b)** Normalized trend of published papers *per* year in the timeframe 2000–2023 (till December 2023) containing the overmentioned keywords combination. **c)** Number of published papers in the timeframe 2000–2023 (till December 2023) containing the keywords combination *per* country. Legend: blue stands for "plant" AND "extraterrestrial" (PE), orange stands for "plant" AND "mars" (PMa), grey stands for "plant" AND "moon" (PMo), yellow stands for "plant" AND "BLSS" (PB), sky-blue stands for "plant" AND "astrobiology" (PA) and green stands for "plant" AND "ISRU" (PI). Data source: Scopus. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

D'Alelio et al. [39] to obtain a tidied Document Term Matrix (DTM). Non-accessible, non-readable or uninformative publications were eliminated [40], limiting our approach to author keywords for excluding biases in the information-flow network, eventually due to not-strictly related words, repetitions, words' similarity because of endings, conjugations, and declensions [38].

The most frequent words that emerge from the keyword combinations Scopus search are shown in Tables S1 and S2. Beyond the clearly related single words to the keyword combinations such as *extraterrestrial*, *mars*, *moon*, *plant* and *space* it turns out that the most frequent single words across the combinations are *conditions*, *growth,* support and *water* (except for PA and PI). Concerning *growth* frequency, we can observe the term counting of 20, 80, 56 and 61 in PE, PMa, PMo and PB, respectively.

Beyond that, the top frequent bigram is *life_support* among the different keyword combination, suggesting the top interest in space biology on the application in life support systems in long-term space mission perspective (Table S2). *Life_support* is then followed by *plant_growth*, except in PB where it is at the fifth position. However, this result may indicate a clear involvement of plant sciences in the building up of life support systems.

The clustering analysis showed that single words distributed according to topic fields. Bigrams clustering analysis was not performed because of the too small DTMs. In Table S3, we observe a repartition associable to several clusters *per* keywords combination. The only relevant cluster in PE is the first one as grouping of keywords related to plant application on ISS. PMa and PMo clearly produced two recognizable clusters. The first one is a life support in long term mission cluster (cluster 1 in both PMa and PMo) and the second one is an exoplanetary conditions effects on plant cluster as cluster 3 in PMa and cluster 2 in PMo. In PB combination, BLSS subtopics may be recognized as clusters. Cluster 1 indicates soil/substrate employment for BLSS, cluster 2 is about plant biology specifically applied in life support systems, cluster 3 reports the regenerative parts of a BLSS that may be represented by human wastes, cluster 4 focuses on exoplanetary conditions effects and cluster 5 regards possible plant species to be employed.

We performed networking, occurrences and clustering on the 210

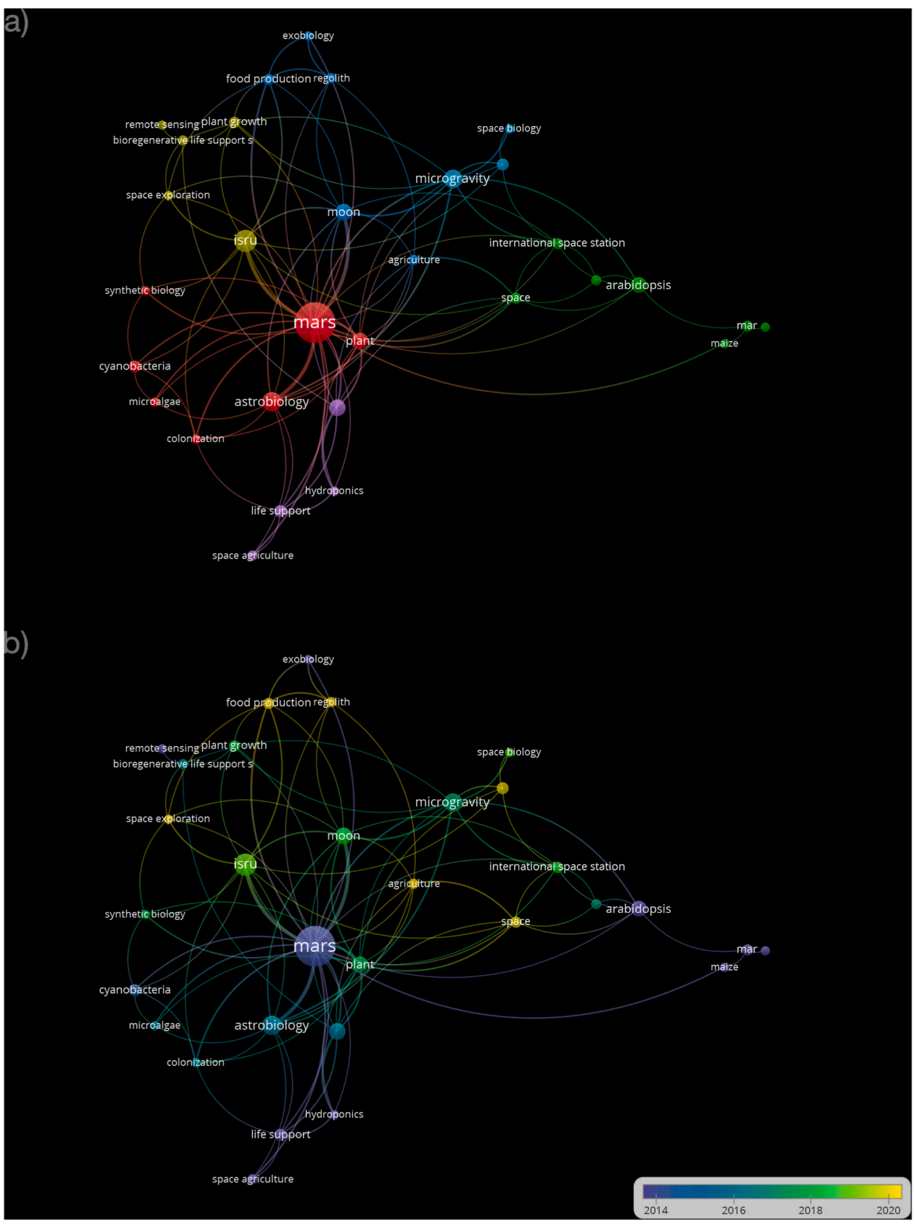

Fig. 2. a) Co-occurrence network map of keywords in the timeframe 2000–2023 (till December 2023) containing the words "plant" AND "mars" (Scopus source). Keywords threshold has been set to 5 co-occurrences. The size of the nodes (keywords) is proportional to the occurrences number in the documents' set. Colors indicate clusters to which keywords are assigned on their reciprocal relatedness. **b)** Overlay of the co-occurrence network map representing keywords on the average occurrence in documents *per* publication year. Color gradient indicates older publication in blue to recent publication in yellow. Color gradient time range is automatically chosen by VOSviewer to highlight major differences through time. Data source: Scopus. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(PE, Fig. S1), 748 (PMa, Fig. 2), 562 (PMo, Fig. 3), 104 (PB, Fig. S2), 100 (PA, Fig. S3) and 84 (PI, Fig. S4) results of the previously mentioned Scopus search through the open source software VOSviewer, elaborating network maps in which keywords are displayed according to their relatedness degree, possibly generating clusters. PE combination displays a total of 664 keywords of which 27 meet the threshold of 3. PMa reports a total of 2108 keywords of which 33 meet the threshold of 5. PMo reports 1664 keywords of which 16 meet the threshold of 5. PB displays 332 keywords of which 23 meet the threshold of 3. PA reports 403 keywords of which 18 meet the threshold of 3. PI reports 180 keywords of which 9 meet the threshold of 3.

Fig. S1a shows clear clustering in the PE keywords combination that are listed in Table S4. Cluster 1 (red, 6 items) focuses on biosignature search and exotic photosynthesis sensing. Cluster 2 (green, 5 items) mainly encompasses astrobiology research topic of life at its limits with extremophiles. Cluster 3 (blues, 4 items) consists in plant space biology major study topics like microgravity and space conditions effects on plant growth. Cluster 4 (yellow, 4 items) focuses on ISS and in general space flight application. Cluster 5 (violet, 3 items) highlighted ISRU in relation to Mars. Fig. S1b reports the last two clusters (6, cyan, 2 items and 7, orange, 1 item) as the most recent, specifically focused on *controlled environment* and *ionizing radiation*. Fig. 2a concerns PMa keywords combination clustering, reported in Table S4. We identify two macro-areas of partially overlapped clusters. The first one is represented by clusters 1 (red, 7 items), 2 (green, 7 items), and 6 (cyan, 3 items) mainly focused on *in situ* resource utilization by using regolith (clusters 1 and 2) to support bioregenerative systems and *in situ* food production. Instead, the other macro-area is centered on space agriculture farming

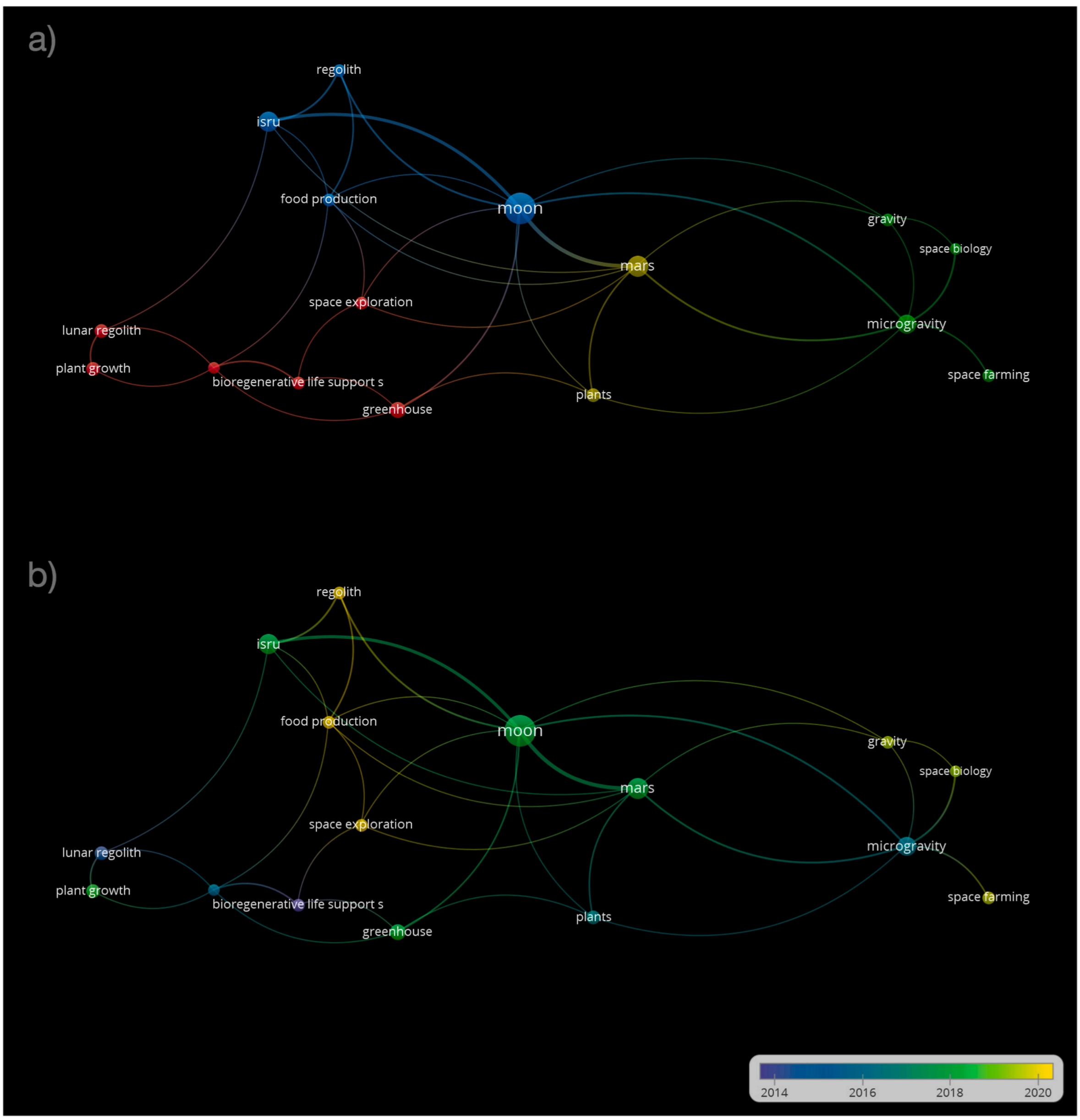

Fig. 3. a) Co-occurrence network map of keywords in the timeframe 2000–2023 (till December 2023) containing the words “plant” AND “moon” (Scopus source). Keywords threshold has been set to 5 co-occurrences. The size of the nodes (keywords) is proportional to the occurrences number in the documents' set. Colors indicate clusters to which keywords are assigned on their reciprocal relatedness. **b)** Overlay of the co-occurrence network map representing keywords on the average occurrence in documents *per* publication year. Color gradient indicates older publication in blue to recent publication in yellow. Color gradient time range is automatically chosen by VOSviewer to highlight major differences through time. Data source: Scopus. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

applied in outer space context (cluster 3, blue, 5 items; cluster 4, yellow, 5 items; cluster 5, violet; 4 items). Fig. 2b shows cluster 4 keyword *in situ resource utilization* and its links to *space exploratio*n, *regolith,* and *food production* are the most recent keyword combinations in the cluster elaboration. Even for PMo keywords combination clustering, we noticed partial overlapping among clusters (Fig. 3a). Cluster 1 (red, 6 items) and 2 (green, 4 items) may be merged on a *space farming*-related topic. Cluster 3 (blue, 4 items) is specifically regarding *in situ* resource utilization for food production, eventually involving lunar regolith. Similarly to Figs. 2b and. 3b shows the links of *isru* to *space exploration* and *food production* as the most recent. Fig. S2a reports PB keywords combination clustering, and since the threshold for co-occurrences is lower, we did not identify defined clusters.

Cluster 1 (red, 7 items) is focused on the *food production* in *space exploration* context (*mars* and *moon*), partially overlapping with cluster 3 (blue, 5 items), reporting the keyword *soil-like substrate* and referring again to *life* support *systems*. Cluster 2 (green, 7 items) may be more general and non-defined. Fig. S2b reports that cluster 1 and cluster 3 keywords connection represents the most recent co-occurrences. Fig. S3a shows the PA keywords combination. The set threshold is 3 and consequently, clusters may overlap. Cluster 1 (red, 5 items) may be focused on microgravity and radiation effects in the space biology research field. Cluster 2 (green, 4 items) may refer to the solar system in general. Cluster 3 (blue, 3 items) focuses on extremophiles and Cluster 4 (yellow, 2 items) on the search for biosignatures on Mars. None of the clusters is related to space plant biology or space farming from ISRU perspective. Fig. S3b elaborates on *extremophiles* and *magnetic field* as the most recently occurred keywords. Fig. S4a reports the PI keyword combination. The threshold is still 3. All the clusters may be overlapped and did not show relevant differences in terms of keyword topics. Cluster 3 is the most recent one, according to the VOSviewer elaboration (Fig. S4b).

4. Discussion

The bibliometric analyses showed a slight general increase in publications in the last ten years only for the keyword combinations PMa and PMo. This trend may be related to the restart of Mars exploration missions in 2011 with the Mars Science Laboratory's Curiosity [43]. It may indicate the interest of the scientific community toward plant biology application in exoplanetary conditions in the perspective of long-term space missions [8]. RStudio analyses clearly showed a rising publications about plants in exoplanetary contexts to sustain human life, specifically for PE, PMa and PMo. Indeed, the keywords *plant*, *life*, support, *system* and *growth*, and bigrams *life_support* and *plant_growth* were always classified in the first ten positions among the different keyword combinations. Additionally, RStudio and VOSviewer clustering agree with the shifting interest towards the long-term space mission and food production perspective, where BLSS and ISRU represent the main objects of research and application field of plant space biology [8,9]. According to VOSviewer's elaboration, ISRU is the most recent co-occurring keyword in PMa and PMo. Despite this, our Scopus searches on those precise keyword combinations (PB and PI) did not provide relevant information since they were small starting DTMs. This probably means that BLSS and ISRU, as main topic keywords, still represent small publications niches. However, since both occur in the two most relevant analyzed keyword combination, we may suggest that BLSS and ISRU are possible ongoing trending topics in plant space biology [9,44].

Regarding BLSSs and their employment in space missions, two relevant sub-fields may be recognized in the literature [44]. The first one would focus on short-term missions involving fast-growing crop production to integrate with the astronauts' diet [45–50]. The second would be centered on stable and staple crops providing an essential diet to astronauts, in terms of functional food, during long-term space missions [51–55]. On this specific issue, the study of space multi-stressor effects on plants is fundamental to understanding the feasibility and application of a plant species from a space mission perspective. Our bibliometric analyses indicate that topic area related to space environmental constraints gained attention in the 2016–2020 time frame, with more publications among the analyzed keyword combinations. Afterward, in 2020–2023, publications shifted towards *ISRU*, *space exploration*, and *food production*. Considering long-term Lunar and Mars-based missions, ISRU application will be decisive for plant cultivation in space conditions. In particular, treating Lunar and Martian substrate with fertilizers and amendments [56,57], may represent an appropriate *in-situ* solution to make possible plant cultivation and food production [8], limiting the refurbishment of resources from Earth not affordable because of the high costs, extreme energy requirements and difficulty to plan and execute launches [18,19]. The ISRU approach integrated with BLSS studies is likely the most realistic and viable solution to guarantee sustainable fresh food production in extra-terrestrial environments [8].

A comparison between our bibliometric analyses and the most recent publications on the topic reveals several knowledge gaps that still need to be addressed by the scientific community. More specifically, the keyword '*water*' appears in the first ten positions for PE, PMa, and PMo keyword combinations elaborated on the single word basis by RStudio, while considering the bigram approach and clustering elaborations, it occurs only once time in cluster 4 for PE combination. The report of our bibliometric analysis agrees with the knowledge gaps evidenced in the most recent publications of [8,9,44]. Water represents a limited resource in space, and it is necessary to understand fluxes within regolith-based substrates integrated into plant systems under microgravity. Water dynamics in extraterrestrial soil are fundamental for mineral weathering and organic matter decomposition. Consequently, these processes significantly impact the biogeochemistry, nutrient availability, and plant growth in extraterrestrial habitats.

Single words such as conditions, gravity, radiation, or effects, as well as clusters 1 from PE, 3 from PMa, 2 from PMo, 4 from PB in RStudio elaboration and 3 and 6 from PE, 5 from PMa, 3 from PMo, 3 from PB and 1 from PA in VOSviewer elaboration, likely indicate a well-defined research branch focused on the effects of extraterrestrial factors on plant growth and physiology, even if it has been possible to identify the need to expand investigations in the specific topic of plant physiological response to soil media [8,9,58,59]. Furthermore, a relevant degree of uncertainty also regards the choice of the most suitable crop candidate to be cultivated in extraterrestrial conditions. The potato and soybean species, vital sources of carbohydrates and protein, respectively, are highly desirable but require high amounts of nutrients, water, and other resources to be cultivated in space [9]. Consequently, the next BLSS and ISRU studies must address the cultivation requirements to obtain sustainable crop yields, also considering the nutraceutical contribution of the species to astronauts' diets. Considering this vital aspect, improving cultivar selection and modulating the ecological factors (i.e. light, temperature, relative humidity) during plant growth in a closed environment may be crucial for optimizing resource-use-efficiency for plant cultivation in space missions and fitting specific requirements [8,9,58–61].

Our network multi-analysis also evidenced a knowledge gap related to plant-substrate interactions about bio-stimulants and amendments utilization in diverse substrates, including space-soil simulants, from a BLSS/ISRU perspective. Specifically, introducing a selected plant microbiota to enhance growth and yield on regolith substrate is promising but still uninvestigated [18,19,44,58,62], representing a critical point on which great efforts must be concentrated. Based on our keyword selection, the provided analysis has revealed that currently only one work referred to space-viable PGPB [32], and few papers propose bacteria inoculation applications on regolith [63–65].

5. Conclusions

Our results highlighted an increasing trend of publications with the keyword combinations PMa and PMo in the last 10 years. Bibliometric analyses clearly showed the high frequency of keywords related to the specific topic 'Life Support Systems' and related research on plant cultivation in the exoplanetary context. We specifically have observed a shifting interest from the research area of space stressor effects on plants towards ISRU application in BLSS for future space missions and food production perspective in the period from 2016 to present. Building up BLSS is a complex multi-disciplinary effort that extends across generation and is mandatory for future missions to the Moon and Mars. Cooperation among different scientific areas and disciplines will bring advances for space exploration, also producing benefits for our planet, especially regarding extreme environments providing solutions to manage the resource overexploitation. Furthermore, our bibliometric network analysis also provides information about scientific knowledge gaps that should be addressed to proceed forward in the plant space research field, optimizing the scientific community's efforts. Based on selected keywords in the literature, we identify four sub-topics that need further investigations, especially in the framework of BLSS/ISRU perspective, related to water dynamics in extraterrestrial environments, plant physiological response on space-soil simulants, plant-substrate interaction with fertilizers, and plant/substrate microbiome.

CRediT authorship contribution statement

Christian Lorenz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Bruno Hay Mele:** Methodology, Writing – review & editing. **Carmen Arena:** Conceptualization, Investigation, Supervision, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actaastro.2024.05.022.

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