FrontAg#Nexus

## Impact of Climate-Smart and Water-Saving Frontier Agriculture on the WEFE Nexus in Arid Mediterranean Regions

# D1.1: Systematic literature review (SLR) of frontier agriculture systems and empirical evidence in the Mediterranean Region

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PRIMA
PARTNERSHIP FOR RESEARCH AND INNOVATION
IN THE MEDITERRANEAN AREA

Co-funded by the European Union

**This project (GA n° [2242]) is part of the PRIMA program supported by the European Union.**

## Document Information

| | |
|---|---|
| **Grant Agreement No.** | 2242 |
| **Project Acronym** | FrontAg Nexus |
| **Project Title** | Impact of Climate-Smart and Water-Saving Frontier Agriculture on the WEFE Nexus in Arid Mediterranean Regions |
| **Call** | PRIMA Call 2022 Section 1 NEXUS WEFE IA |
| **Start – ending date \| Project Duration** | 01 May 2023 – 30 April 2026 \| 36 months |
| **Project Website** | frontagnexus.eu |
| **Project Coordinator** | Gertrud Buchenrieder [Universität der Bundeswehr München (UniBw M)] |
| | |
| **Work Package** | WP1-Conceptual and empirical analysis of frontier agriculture in the Mediterranean Region |
| **WP Lead Beneficiary** | BGU (P4) |
| **Deliverable \| Version \| Status** | D1.1 - Systematic literature review (SLR) of frontier agriculture systems and empirical evidence in the Mediterranean Region |
| **Lead Authors** | Elisa Appolloni, Giuseppina Pennisi, Vito Aurelio Cerasola (UNIBO) |
| **Deliverable type \| Dissemination level** | R – Report \| PU – Public |
| **Due Date of Deliverable** | 31 October 2023 \| Date submitted \| 1 November 2023 |
| **Version \| Status** | [Final] |
| **Contributors** | Elisa Appolloni, Giuseppina Pennisi, Vito Aurelio Cerasola (UNIBO); Wubneshe Biru, Gertrud Buchenrieder (UniBw M); Tanay Sıdkı Uyar, Yusuf İslam Yavuz (EUROSOLAR Türkiye) |
| **Reviewer(s)** | Tanay Sidki Uyar, Quality Manager (EUROSOLAR Türkiye) |

*Deliverable type: R: Document, report (excluding the periodic and final reports); DEC: Websites, press & media actions, videos, etc; OTHER: Software, etc.; Dissemination level: PU: Public; SEN: Sensitive; CI: Classified*

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## Document History

| Version | Changes | Date | Contributor |
|---|---|---|---|
| 0.0 | First draft, UNIBO contribution | 14/09/2023 | Elisa Appolloni, Giuseppina Pennisi, Vito Aurelio Cerasola (UNIBO) |
| 0.1 | First draft, EUROSOLAR TÜRKİYE contribution | 18/09/2023 | Prof. Dr. Tanay Sıdkı Uyar, Yusuf İslam Yavuz (EUROSOLAR Türkiye) |
| 0.2 | First draft, UniBw M contribution | 25/09/2023 | Wubneshe Biru, Gertrud Buchenrieder (UniBw) |
| 1.0 | Final editing | 31/10/2023 | Wubneshe Biru, Gertrud Buchenrieder (UniBw M) |

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# Executive Summary

The present Systematic Literature Review (SRL) on frontier agricultural solutions and empirical evidence thereof in the Mediterranean Area, aims at establishing which frontier agricultural technologies are practiced, their technological readiness level (TRL), business readiness level (BRL), and social readiness level (SRL), costs and benefits, productive capacity, ecosystem services, sectorial polices and key performance indicators (KPIs).

In particular, the SRL aims at answering the following research questions:

**(1)** Is there evidence that frontier agriculture is capable of increasing **circularity** in the Mediterranean area?

**(2)** Is there evidence that frontier agriculture is capable of increasing **sustainability** in the Mediterranean area?

**(3)** Is there evidence that frontier agriculture can improve farm household welfare, particularly **food and nutrition security (FNS)** in the Mediterranean area?

**(4)** What are the existing variations in frontier agriculture regarding various **readiness levels**:

4a) TRL,

4b) BRL, e.g., upfront and running costs, labor requirements, yields, market integration, etc., and

4c) the SRL, e.g., normative and cultural acceptance among different stakeholder groups, such as women, migrants/refugees, youth, etc.?

**(5)** Which **KPIs** at the micro-level could be useful for demonstration pilots to estimate the effect of frontier agricultural solutions on the water-energy-food-ecosystem (WEFE) Nexus?

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## List of Abbreviations

| | |
|---|---|
| BEP | Breakeven point |
| BRL | Business Readiness Level |
| BSF | Black Soldier Fly |
| CAGR | Compound annual growth rate |
| CEA | Controlled Environmental Agriculture |
| °C | Degree Celsius |
| DWC | Deep Water Culture |
| ECR | Economic Conversation Rate |
| EU | European Union |
| GHG | Greenhouse Gas |
| ICTA | Institute of Environmental Science and Technology |
| IoT | Internet of things |
| KPI | Key Performance Indicator |
| LCD | Liquid Crystals Display |
| LED | Light Emitting Diode |
| NFT | Nutrient Film Technique |
| NPK | Nitrite, potassium, phosphorus |
| OMW | Olive Mill Wastewater |
| PRIMA | Partnership for Research and Innovation in the Mediterranean Area |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| RAS | Recirculating Aquaculture Systems |
| RH | Relative humidity |
| SRL | Social Readiness Level |
| TRL | Technological Readiness Level |

# 1 Introduction

Climate change is profoundly impacting the conditions in which agricultural activities are conducted. In every region of the world, plants, animals, and ecosystems are adapted to the prevailing climatic conditions, meaning that even a little change can result in major impacts. Climate change can have both direct impacts (that are directly caused by a modification of physical characteristics, such as temperature levels) and indirect impacts (that affect production through changes in other species such as pollinators, pests, disease vectors, invasive species) on agricultural production systems (FAO, 2015). It was demonstrated that climate change has already negatively affected wheat, maize and rice yields in many regions and also at global level (Lobell et al., 2011). Knox et al. (2012) reported that climate change will reduce average crop yields in Africa by 2050, particularly reducing wheat yields by 17%, sorghum by 15%, millet by 10%, and maize by 5%. Such reductions are not only a matter of higher air temperatures but also limited water availability during the growing season, more frequent and intense heat events (which are most damaging during flowering, Müller and Elliott, 2015), and accelerated phenology, can lead to reduced biomass production. Climate change effects take on an even greater dimension when we consider that global hunger remained relatively unchanged from 2021 to 2022, but is still far above pre-COVID-19-pandemic levels, affecting around 9.2% of the world population in 2022, compared with 7.9% in 2019. It is estimated that between 691 and 783 million people in the world faced hunger in 2022 (FAO, 2023). This global trend hides substantial differences at the regional level: for example, hunger increased throughout all subregions of Africa in 2022 (FAO, 2023), involving the 20% of the population in Africa.

In this context, new resilient and sustainable forms of agricultural practices incorporating a “circular economy” model for food production should be promoted in order to help solving food and nutrition security (FNS) challenges and make food production systems more sustainable and resilient. Frontier agricultural technologies can contribute in reaching these goals, because they do not require a lot of arable land or significant water resources, can be managed in almost closed systems, contribute less to greenhouse gas (GHG) emissions, and have an overall limited impact on the environment. The benefits of frontier agricultural technologies were highlighted by Verner et al. (2021): increased domestic production of nutritious foods and feed; reduced waste and pollution compared with the linear production model; improved sustainability of local food systems and natural resources because of less water requirements, limited impact on land loss and biodiversity degradation, and fewer GHG emissions during the food and feed production process compared with traditional agriculture; improved soil health through application of organic fertilizers consisting of the insect manure (frass) produced during the insect farming process; improved macroeconomic situations and increased national savings of hard currency through reduction of domestic reliance on protein imports for food and feed; increased access to jobs for women and young adults, higher incomes, and better livelihoods, particularly along the food value chain; improved peacebuilding and resilience to fragility, conflict, and violence through the creation of more stable and sustainable food supply chains that provide economic opportunities and require fewer natural resources.

FrontAg Nexus responds to the challenge to reduce the pressure on the water, energy, food, and ecosystems (WEFE) Nexus (**Figure 1**), including biodiversity by identifying sustainable frontier agriculture (**Figure 2**). Several forms of frontier agriculture have been explored, namely, hydroponics (i.e., in the form of different soilless or substrate-based plant cultivation systems), aquaponics (i.e., combining recirculating aquaculture systems (RAS) and hydroponics), insects farming and vermiculture/vermicomposting (both for animal feed or substrate/compost production), and saline agriculture. Hydroponics enables to grow plants out of soil, with roots directly submerged in a nutrient solution (temporary or for the entire growing cycle) or with the use of a medium (usually an inorganic substrate).

**What is WEFE Nexus?**

The WEFE Nexus refers to the interconnectedness of water, energy, food, and ecosystems, highlighting the need for integrated approaches to address their interdependencies and achieve sustainable resource management.

**Figure 1: What is the WEFE Nexus?**

Frontier agriculture is an innovative farming approach that uses advanced technologies like hydroponics, aquaponics, insect farming, and vermicomposting to improve resource efficiency and sustainability. It aims to address challenges in traditional agriculture, promote food security, and reduce pressure on water, energy, and land resources.

**Figure 2: Definition of frontier agriculture**

There is a variety of **hydroponic systems**, from simple to sophisticated and from open to close, and the most adopted are deep water culture, ebb and flow, drip method, nutrient film technique (NFT), and aeroponics. Hydroponics is more productive and efficient than conventional farming (Orsini et al., 2013; Orsini et al., 2020), also requiring fewer amounts of pesticides (Resh and Howard, 2012) and water resources (Michelon et al., 2020). It is a versatile cultivation system that can be adopted also in densely populated urban areas, requiring up to 75% less space than conventional farming methods (Heredia, 2014).

**Aquaponics** produces fish protein and crops, avoiding the negative impact of water depletion from aquaculture or on-soil crop farming. Closing the water and nutrients loop by combining recirculating aquaculture systems (RAS) with hydroponics enables to increase animal welfare and food productivity while reducing environmental stress. Aquaponics uses 90% less water than conventional farming. Aquaponics is a generally profitable and environmentally sustainable food production technology (Benjamin et al., 2021). Insect farming is a rapidly growing industry. Analysts estimate that the global insect feed market size will increase from US$ 621.8 million in 2018 to US$ 1,011.5 million in 2025, a 7.3% CAGR (360 Market Updates 2019).

Indeed, increasing pressure to find new ways to feed the growing global population has resulted in a growing interest in **insect farming**. The number of insects identified as suitable for domestication is increasing. Crickets, mealworms, black soldier fly (BSF) larvae, housefly larvae, palm weevil larvae, and mopane caterpillars are the most commonly farmed insects in African countries. BSF larvae breeding as a means to produce crude protein for feed and substrate/humus is still a nascent business sector in the Mediterranean Region. BSF larvae can be produced at large-scale in industrial facilities but also by non-mechanized systems. Crude protein from BSF farming can replace approximately 50% of the fishmeal used in aquaculture and also for poultry and other livestock (Tomberlin et al., 2015).

**Vermiculture/vermicomposting**, which depends on the use of worms to accelerate the upcycling of organic waste (e.g., sewage sludge from aquaponics or agricultural residues) into soil enriching substrate/humus, is socially acceptable all over the world. Vermicomposting is not only environmentally sustainable but also economically viable (Bajsa et al., 2004), but seems to have lost traction in small-scale farming systems. Especially for larger agricultural economies, such as Morocco, insect farming has great potential for bio-fertilizer while reducing water use and greenhouse gases (GHG) emissions (Verner et al., 2021).

Within this framework, the aim of this Deliverable 1.1 (WP1 “Conceptual and empirical analysis of frontier agriculture in the Mediterranean Region”) is to develop a systematic literature review (SLR) on frontier agriculture in the Mediterranean Region to reveal which frontier agriculture technologies are practiced (or not).

In particular, the SRL aims at answering the following research questions:

**(1)** Is there evidence that frontier agriculture is capable of increasing **circularity** in the Mediterranean area?

**(2)** Is there evidence that frontier agriculture is capable of increasing **sustainability** in the Mediterranean area?

**(3)** Is there evidence that frontier agriculture is capable of improving farm household welfare, particularly **food and nutrition security** (FNS) in the Mediterranean area?

**(4)** What are the existing variations in frontier agriculture with regard to various **readiness levels**:

4a) technical readiness level (TRL),

4b) business readiness level (BRL), e.g., upfront and running costs, labor requirements, yields, market integration, etc., and

4c) the social readiness level (SRL), e.g., normative and cultural acceptance among different stakeholder groups, such as women, migrants/refugees, youth, etc.?

**(5)** Which **key performance indicators** (KPIs) at the micro-level could be useful for demonstration pilots to estimate the effect of frontier agricultural solutions on the water-energy-food-ecosystem (WEFE) Nexus?

The SRL is crucial for evaluating the performance of WEFE Nexus outcomes of frontier agricultural innovations (i.e., 10+ demonstration cases[1]). Furthermore, frontier agricultural innovations are prime examples of the multisolving approach, in other words multiple challenges can be addressed with a single investment of time and money. The multisolving approach has great relevance in this era of complex, interlinked, social, and environmental challenges as reflected by the thrive for a sustainable WEFE Nexus (Sawin, 2018). The results of the SLR allow for tailoring and optimizing the demonstration pilots, established by FrontAg Nexus, where these frontier agricultural innovations are not available. This will improve of the capacity of development activities and selection of appropriate agro-ecological improvements.

[1] A demonstration case is defined as socio-economic innovation experiment; thus, it is not enough to consider technical readiness but also business and social readiness levels (i.e., TRL, BRL, and SRL). In the Mediterranean countries engaged in FrontAg Nexus, existing frontier agricultural innovations such as hydroponics, aquaponics, insect farming, and vermiculture/vermicomposting systems will be identified to establish demonstration cases. Where these frontier agricultural innovations are not available, FrontAg Nexus will establish new demonstration pilots as ‘proof of concept’ with local innovation actors.

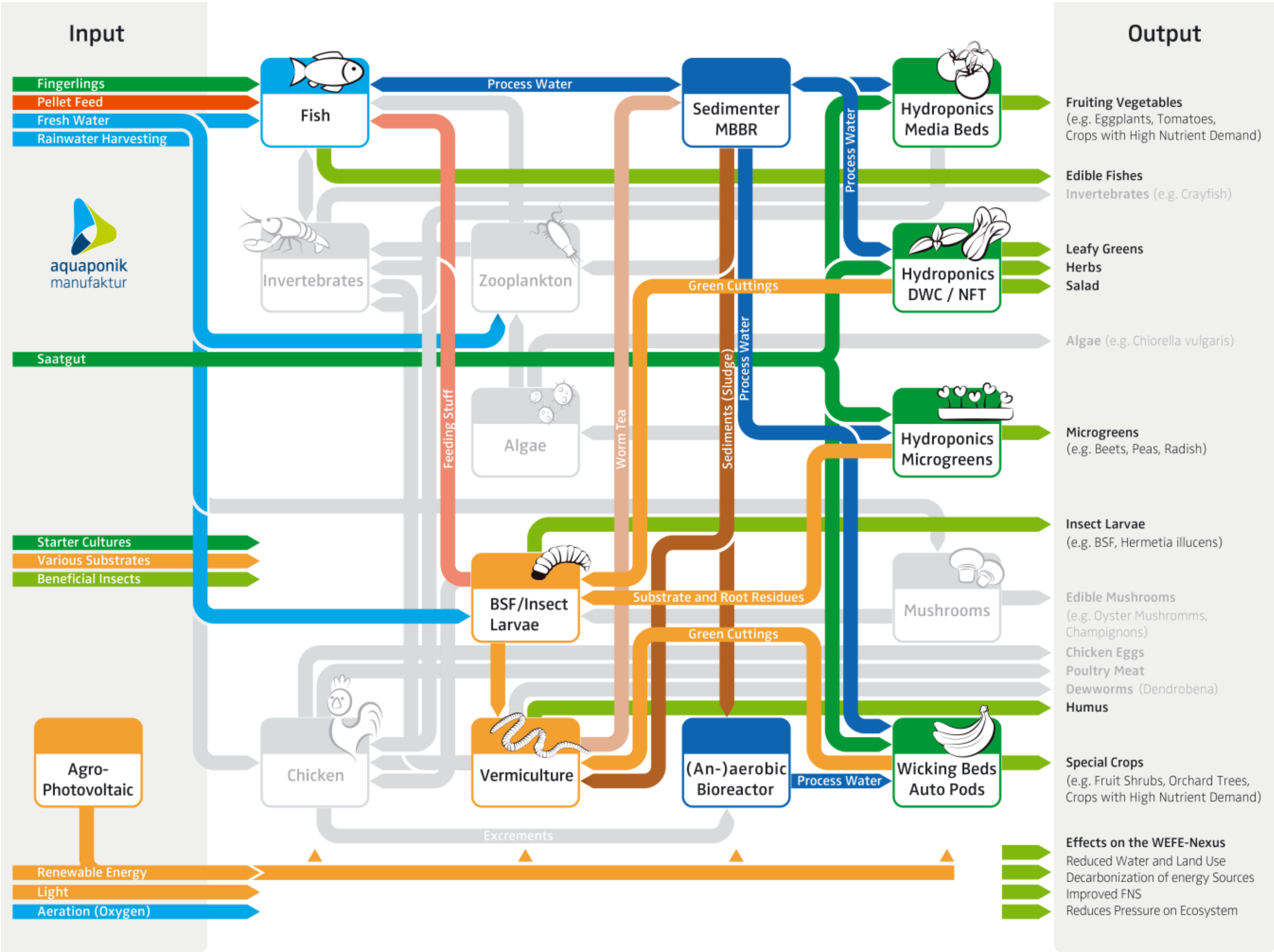


**Figure 3: Multisolving approach inherent to frontier agriculture**

Source: APM (P2) ©

Note: Chicken rearing is not explicitly mentioned in the FrontAg Nexus proposal as this is not perceived as frontier agriculture. Nevertheless, combining it with frontier agriculture accelerates the positive Nexus effects.

The greyed-out tiles could be part of the multisolving approach inherent to frontier agriculture, but are not foreseen in FrontAg Nexus.

DWC = deep water culture; MBBR = moving bed biofilm reactor; NFT = nutrient film technic

# 2 Methodology

## 2.1 PRISMA approach

The SLR was developed basing on a PRISMA approach as schematized in Figure 4.

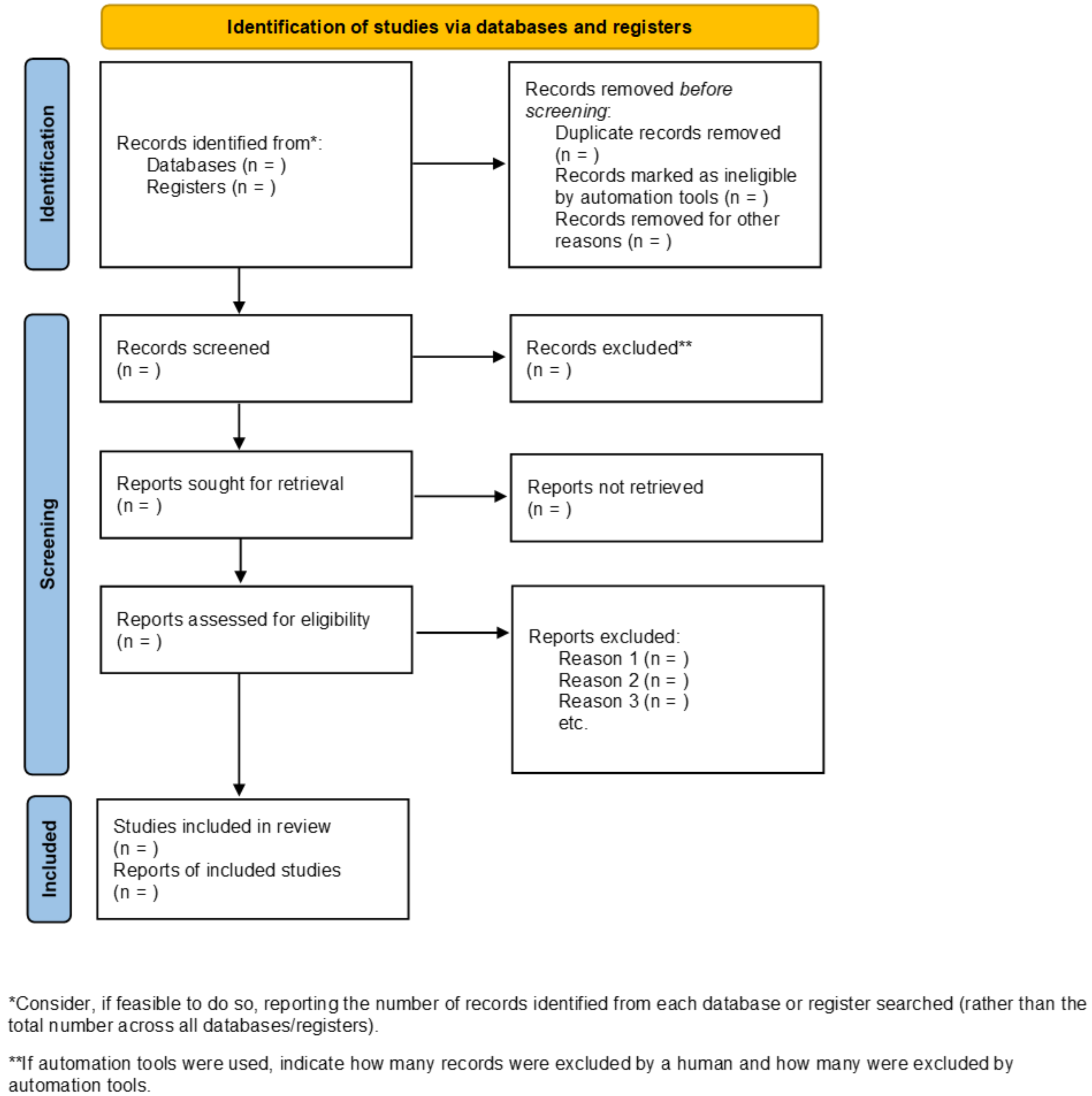


Figure 4: PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only

More details on PRISMA approach are reported at the following links:

- https://guides.lib.unc.edu/systematic-reviews/write
- http://www.prisma-statement.org/PRISMAStatement/FlowDiagram?AspxAutoDetectCookieSupport=1

The SLR was conducted basing on 9 phases by Gough (2007):

- establishing the review question
- defining inclusion and exclusion criteria,
- articulating the search strategy, including information sources,
- screening the articles to see if they meet the inclusion and exclusion criteria,
- reporting the results of the search strategy, usually through a flowchart,
- extracting relevant data from included studies,
- assessing the methodological quality or rigor of the included studies,
- synthesizing, either quantitatively or qualitatively, the collective evidence of the included studies, and
- drawing concluding and communicating these findings in a manner relevant to the readership.

## 2.2 Topic and keywords

The SLR was developed investigating 8 thematic researches for each of the 6 frontier agriculture cultivation systems promoting circularity and sustainability.

The identified frontier agriculture cultivation systems are:

- Hydroponics and controlled environment systems (e.g., vertical farming) (with a specific focus on fodder and nutraceutical plants production, beside vegetable crops),
- Aquaponics,
- Vermiculture,
- Insect farming,
- Rooftop agriculture,
- Saline agriculture.

The thematic researchers analyzed for frontier cultivation system are:

- Food and feed production,
- Waste,
- Energy efficiency, renewable energy sources and energy transition,
- Ecosystem services and carbon footprint;
- Business, social, and technical readiness level.

The searching strings have been constructed combining 3 groups of keywords:

1. Keywords on thematic researches;
2. Keywords on frontier agriculture cultivation systems;
3. Keywords on PRIMA Mediterranean countries (including Jordan);

Each searching has been done for each thematic research, repeating the searching for each frontier agriculture cultivation system. Table 1 reports the combination of keywords used as searching strings.

**Table 1: Combination of keywords for searching strings.**

| 1. Thematic researches | | 2. Frontier agri-culture cultivation systems | | 3. PRIMA Mediterranean countries |
|---|---|---|---|---|
| **1. Food and feed production:**<br>“food product*” OR “yield” OR “fodder” OR “nutraceutical*” OR “vegetable crop*” OR “feed” OR “medicinal*” OR “officinal*” OR “aromatic*” OR “forage” OR “animal feed” OR “vegetable*”<br>**2. Waste:**<br>“circularity” OR “resource* efficiency” OR “resource* optimization” OR “waste*” OR “waste*reuse” OR “waste* recycle*” OR “closed loop” OR “recycle*” OR “reuse” OR “byproduct*” OR “by-product*” OR “compost”<br>**3. Energy efficiency, renewable energy sources and energy transition:**<br>“sustainable energy” OR “carbon neutrality” OR “solar energy” OR “photovoltaic system*” OR “energy management” OR “energy conservation” OR “energy efficiency” OR “energy consumption*” OR “energy management” OR “green econom*” OR “carbon emission*” OR “PV solar power plant*” OR “greenhouse*”<br>**4. Ecosystem services and carbon footprint:**<br>“carbon footprint” OR “resource depletion” OR “amenity values” OR “conservation” OR “sequestration” OR “recreation” OR “externality” OR “inorganic fertilizer* reduction” OR “reduction of inorganic fertilizer*” OR “mineral fertilizer* reduction” OR “reduction of mineral fertilizer*” OR “reduction of pesticide*” OR “pesticide* reduction” OR “active ingredient*” OR “reduction of emission*” OR “emission* reduction” OR “emission* saving*” OR “biodiversity” OR “Circularity” OR “sequestration” OR “conservation” OR “water use efficiency” OR “water saving*” OR “irrigation” OR “closed loop*” OR “water reuse” OR “water recycle”<br>**5. Business, social, and technical readiness level:**<br>"circularity" OR "TRL" OR "SRL" OR "BRL" OR "technical readiness" OR "soci* readiness" OR "market*" OR "business readiness" OR "micro enterprise*" OR "SME" OR "small and medium enterprise*" OR "small scale" OR "medium scale" OR "large scale" OR "commercial farm*" OR "subsistence farm*" OR "sale*" OR "cost benefit" OR "profit*" | **AND** | **1. Hydroponic:**<br>“hydroponic*” OR “soilless” OR “aeroponic*” OR “controlled environment” OR “vertical farm*” OR “plant factor*” OR “building integrated agriculture”<br>**2. Aquaponic:**<br>“aquaponic*” OR “recirculating aquaculture*” OR “RAS”<br>**3. Vermiculture:**<br>“vermiculture” OR “vermicompost”<br>**4. Insect farming:**<br>“insect farming” OR “insect production”<br>**5. Rooftop agriculture:**<br>“rooftop greenhouse*” OR “rooftop farm*” OR “rooftop agriculture” OR “building integrated agriculture”<br>**6. Saline agriculture:**<br>“saline agriculture” OR “saline farm*” OR “biosaline agriculture” OR “biosaline farm*” OR “halophytic plant*” | **AND** | "Mediterranean" OR “Spain” OR “France” OR “Italy” OR “Malta” OR “Slovenia” OR “Croatia” OR “Greece” OR “Turkey” OR “Lebanon” OR “Israel” OR “Cyprus” OR “Morocco” OR “Algeria” OR “Tunisia” OR “Egypt” OR “Jordan” |

## 2.3 Identification and screening steps

The identification of papers was based on the Scopus database by applying the above-mentioned searching strings. Only articles published 2018 and onwards, in English, containing the identified keywords in the title, keywords or abstract were considered for selection.

The first screening phase consisted in the evaluation of abstracts and titles of identified articles, excluding those papers that:

- did not belong to 1° or 2° quartiles of Scimago Journal & Country Rank (SJR);
- were not from PRIMA countries of Mediterranean area, including Jordan;
- presented a repetition within thematic research;
- were not coherent with the aims, research questions and thematic researches.

The second screening phase consisted in an in-depth evaluation of articles contents, excluding those articles that did not report empirically based measurable results (e.g., literature reviews, except if the literature review is also reporting data from empirical papers).

# 3 Results and discussion

After the screening of articles, the following number of articles were retained (Table 2):

- 48 articles for “Food and feed production” topic,
- 12 for “Waste”,
- 19 for “Energy efficiency, renewable energy sources and energy transition”,
- 32 for “Ecosystem services and carbon footprint”, and
- 7 for “Business, social, and technical readiness level”.

The final selected papers (sorted by thematic search) have been collected in a common library using Zotero software (Library).

**Table 2: Excluded papers after first and second screening**

| Thematic research | Identified papers | First screening | Second screening | Final selected papers |
|---|---|---|---|---|
| Food and feed production | 261 | -192 | -23 | **46** |
| Waste | 74 | -59 | -3 | **12** |
| Energy efficiency, renewable energy sources and energy transition | 186 | -128 | -39 | **19** |
| Ecosystem services and carbon footprint | 152 | -98 | -9 | **32** |
| Business, social, and technical readiness level | 55 | -30 | -13 | **7** |

The yearly, country and cultivation systems distribution for the thematic researches of Food and feed, Waste, and Ecosystem services and carbon footprint, are reported in **Figure 5**, **Figure 6**, and **Figure 7** respectively. Among European Mediterranean countries Spain and Italy are leading the research, with totality of Spanish researches on the topic of Rooftop Agriculture. In case of Mediterranean countries in Northern Africa, Egypt is the one developing more research on frontier agriculture systems.

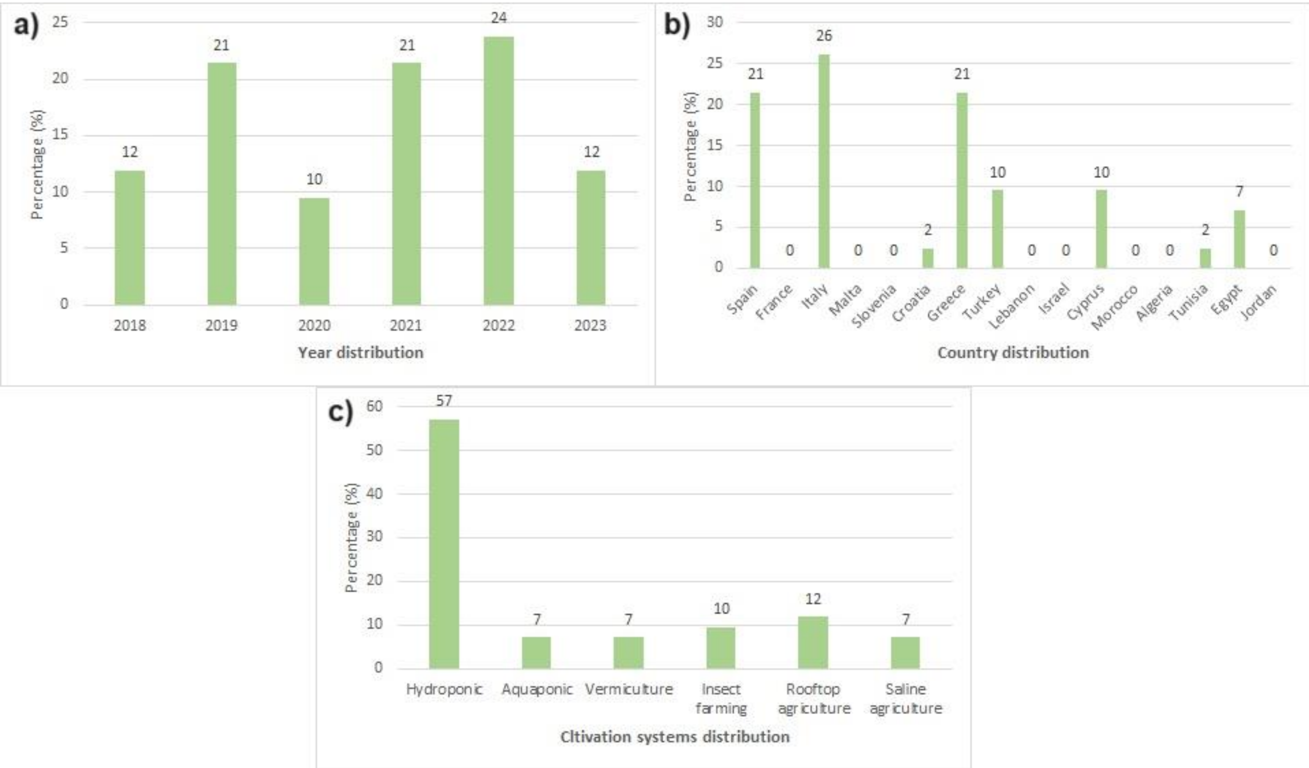


**Figure 5: Year (a), country (b) and cultivation system (c) distribution for collected articles on food and feed thematic research**

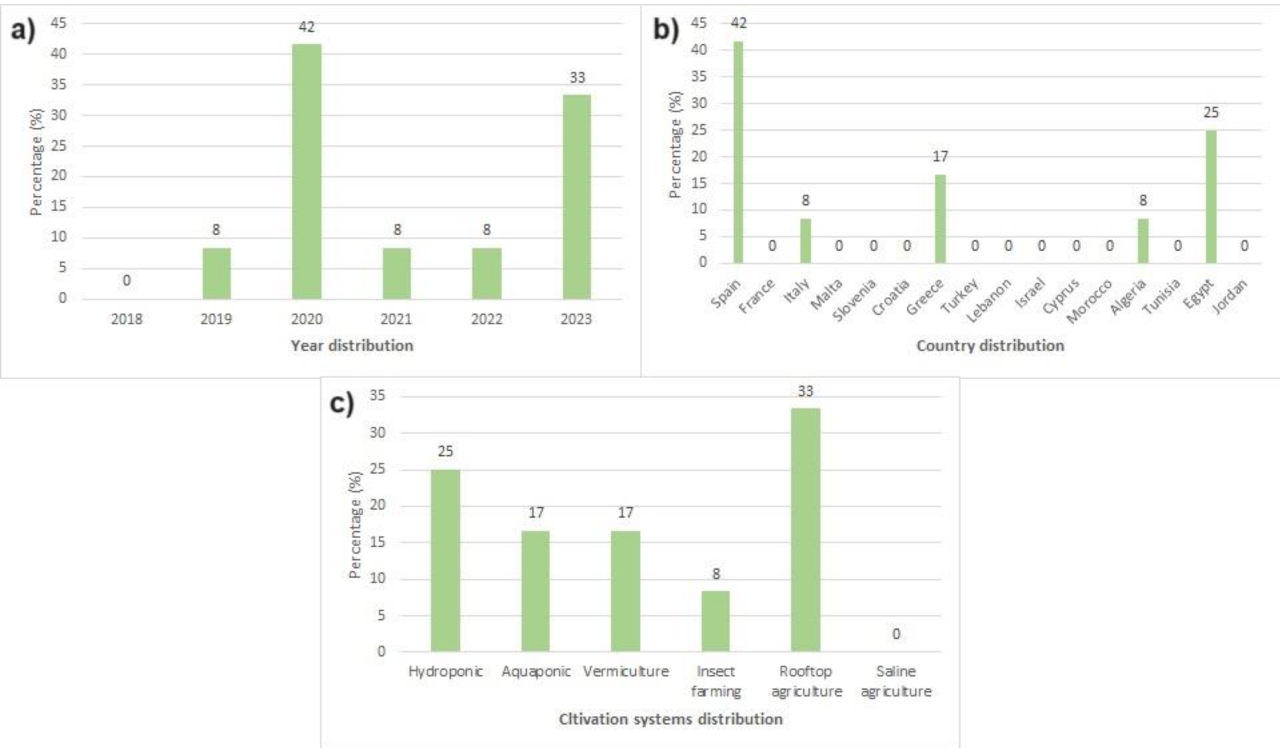


**Figure 6: Year (a), country (b) and cultivation system (c) distribution for collected articles on waste thematic research**

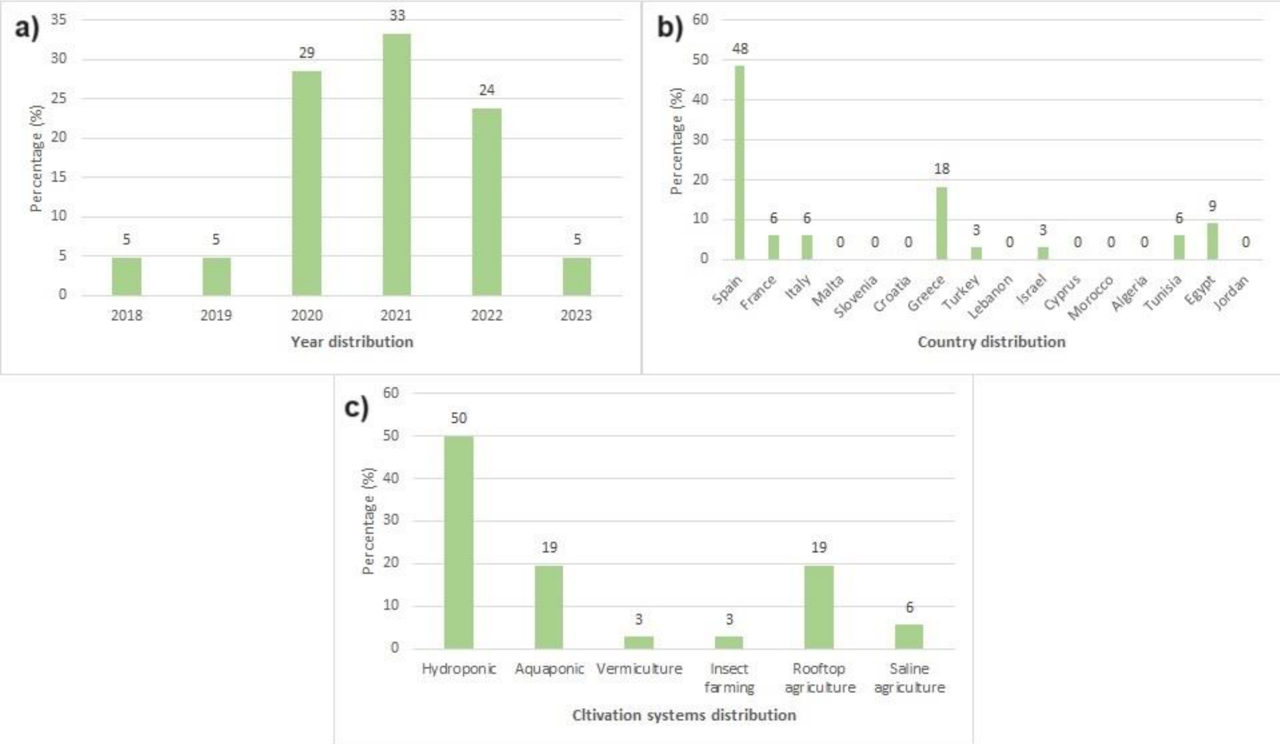


**Figure 7: Year (a), country (b) and cultivation system (c) distribution for collected articles on ecosystem services and carbon footprint thematic research**

## 3.1 Food and Feed

### 3.1.1 Hydroponic

Soil based agriculture is subject to vulnerability to natural disasters associated to climate change, which are going to become more frequent and unpredictable, making yield crops highly variable (Juhász et al., 2020). The inherent variability which characterize on-soil agriculture reverse also to unstable food prices, affecting mainly the people living in condition of social and economic marginality (Wossen et al., 2018). Moreover, arable land availability is threatened by the high urbanization and industrialization rate (Orsini et al., 2013), which clearly conflicts to the need to intensificate the food production to provide healthy food to the growing urban population. In this framework, hydroponic technologies and Controlled Environmental Agriculture (CEA) play a crucial role, since they allow the food production in absence of soil (Savvas et al., 2013). Hydroponic proved to be a real possibility to grow food valorizing non-cultivable sites, which is why it is of interest also for urban agriculture contributing to food security and local food production (Orsini et al., 2013).

Hydroponics system are known to be more efficient than on-soil cultivation, given that they allow for multiple growing cycle along the year by accelerating the crop growth, and with reduced water consumption up to -60% in lettuce cultivation (Martinez-Mate et al., 2018). Rodriguez-Ortega et al. (2019) compared the agronomical and resource efficiency performance of a tomato crop under NFT and perlite growing system. The highest yields were obtained under perlite cultivation but any difference in the water use efficiency was reported. However, high variability in the yield of lettuce and tomato is experienced according to the growing conditions (Table 3).

Peat is among the most used substrates worldwide, and the environmental burden associated to its anthropogenic extraction from ecosystem raises concerns about its sustainability (Petropoulos et al., 2019). Much effort was dedicated on finding alternative growing substrates. For example, recovering byproduct from cotton industry for being used as a growing substrate can be a successful strategy to partially substitute peat, thus promoting circular relationships between industrial and agricultural sectors (Petropoulos et al., 2019).

**Table 3: Productive capacity of hydroponic system as function of growing system and environmental conditions**

| Article | Country | Type of cultivation system | Environmental conditions | Species | Productive capacity |
|---|---|---|---|---|---|
| Moncana et al. (2020) | Italy | Floating system | Greenhouse | Lettuce | 3.2 kg $m^{-2}$ |
| Kılıç et al. (2022) | Turkey | NFT | | | 4.6 kg $m^{-2}$ |
| Martinez-Mate et al. (2018) | Spain | | Open air | | 2.7 kg $m^{-2}$ |
| Neocleous & Savvas (2022) | Cyprus | | CEA | | 3.3 kg $m^{-2}$ |
| Martinez-Mate et al. (2018) | Spain | Soil | Open air | | 2.5 kg $m^{-2}$ |
| Rodriguez-Ortega et al. (2019) | Spain | Floating system | Greenhouse | Tomato | 5 kg $plant^{-1}$ |
| | | Perlite | | | 4.2 kg $plant^{-1}$ |
| | | NFT | | | 3.8 kg $plant^{-1}$ |
| Neocleous & Savvas (2022) | Cyprus | NFT | CEA | | 4.8 kg $plant^{-1}$ |
| Neocleous et al. (2021) | Cyprus | NFT | | | 6 kg $plant^{-1}$ |

Note: NFT = nutrient film technique

On the other hand, the growing interest associated to the consumption of sea fennel (*Crithmum maritimum*) for its nutraceutical properties led Montesano et al. (2018) to find in Posidonia compost a valid alternative to fully replace peat, highlighting that high-saline substrate (such as seaweed-based compost) can be used for halophytic plants. And it is not only a matter of organic substrates, since also the dredged sediments, if properly treated, can be used successfully in basil cultivation to replace partially the peat, even increasing the yield with effect on the quality of the product (Nin et al., 2023). The exploration of alternative substrate to replace commercial ones deserved the attention of further authors, finding in trunk date palm compost (Aydi et al., 2023) or in grape marc compost (Martini et al., 2023; Tassoula et al., 2021) valid alternatives.

Hydroponic system are versatile facilities that can be efficiently used both in open-air conditions (Martinez-Mate et al., 2018; Okasha et al., 2022; Tassoula et al., 2021; Martini et al., 2023) and in protected cultivation, including active or passive climate control. Although in Mediterranean environment the light availability is not commonly considered as a limited resource, the integration of supplemental lighting allows to increase the yield and the fruit dimension in tomato cultivation (Paucek et al., 2020). The Controlled Environment Agriculture (CEA) is widely adopted in Northern Europe for improving light conditions and for satisfying the heating requirement. However, in Mediterranean heating can be required in winter season or during nighttime when the temperature is expected to drop. Baddadi et al. (2019) used a solar air collector to increase temperature during nighttime of an indoor hydroponic greenhouse in Tunisia. In addition to the solar heating, Bouadila et al. (2022) integrated also a cooling system using pipes exchanger with freshwater, with positive effects on the hydroponical growth of fodder. However, Nikolaou et al. (2019) proved that the simple forced ventilation is a valuable cooling strategy for greenhouses in Greece in cucumber cultivation, reducing the cost and enhancing the yield as compared with the adoption of evaporative pad. And it is not only a matter of temperature control: in fact forced ventilation can reduce also the drainage outflow of the nutrient solution. The hydroponic facilities have to cope with the management of the drained nutrient solution, which can be discharged into the environment (open systems) or reused for further irrigation events (closed systems). Despite the high environmental impact associated to the open systems, in several regions of the world, including Mediterranean, they are preferred among growers since the lower cost and technical knowledge required (Santos et al., 2022). In fact, the recirculation of the nutrient solution in closed system determine the accumulation of sodium and chloride that are not absorbed by the plant, thus increasing the salinity of the solution above the tolerance level of the crop, leading to the release of the exhaust nutrient solution into the environment. Although this process is exacerbated in the Mediterranean climate where the warmer temperature stimulates the crop transpiration, a number of authors are proposing alternative strategies for coping to the limits of closed systems. Adopting Decision Support System (DSS) can optimize the recirculation of the nutrient solution in closed systems, maintaining the salinity level below the critical threshold for longer time reducing the discharging into the environment (Neocleosus and Savvas, 2022). An alternative to closed system is the semi-closed systems, that consists on reusing the drained solution from a primary crop in a secondary crop, generally with higher tolerance to high salinity. For example, Santos et al. (2022) found that up to the 50% of the drained solution collected from strawberry cultivation can be reused for lettuce cultivation in NFT system. Alternatively, Dasgan et al. (2023) replaced successfully the 20% of mineral fertilizers with mycorrhizal and beneficial bacterial without any negative effect on the yield of capia pepper. However, besides the hydroponic system chosen, the salinity of water resources is a topic of interest for Mediterranean area, where the groundwater resources are usually characterized by a high level of salinity. While high-salinity is known to improve some qualitative traits of fruits vegetable crops, it is usually associated to yield losses (Rodriguez-Ortega et al., 2019). Notwithstanding, Okasha et al. (2022) found that yield and water productivity can increase when magnetically treated seawater is used in comparison to common freshwater, even though limits in the methodology need to be considered. The research on the adoption of seawater desallinisators is stimulated by Spanish government, aimed at increasing the availability of low-saline water resources. A high energy requirement of desallinisators devices should be highlighted, even if it could be satisfied by the coupling with renewable energy thus reducing the associated environmental burden (Martinez-Mate et al., 2018). The use of desalinized water is economically profitable only in areas where the conventional water resources are highly saline such as in Southern Spain because its proximity to the sea (Martinez-Granado et al., 2022) while in inner areas where the salinity level is generally lower the use of conventional saline water can be more convenient. In this regard, Moncada et al. (2020) used bacterial bio-stimulants to alleviate salt-stress of lettuce cultivation in a floating system, while the choice of new crops more tolerant to salinity a strategy is proposed by a few authors (Maggini et al., 2021; Montesano et al., 2018). Growing new crops is undoubtedly one of the strengths of hydroponic system, given it permits to go along the market reqirements. Indeed, the nutraceutical properties of wild edible species attracted the attention of consumers, and different species were tested such as Chrithmum maritimum (Montesano et al., 2018; Sarrou et al., 2019), Portulaca oleracea (D'Imperio et al., 2020), Rumex acetosa (Ceccanti et al., 2018), Chicorium spinosum (Petropoulos et al., 2019), or Reichardia picroides (Maggini et al., 2021). Despite this, proper agronomic techniques for optimizing the yield of wild species in hydroponics still need to be developed (Ceccanti et al., 2018). On the other hand, the biofortification consist of increasing or decreasing the concentration of specific mineral elements of the nutrient solution, which can ameliorate the nutraceutical properties even of the most common vegetable (Renna et al., 2018, D'Imperio et al., 2020, Buturi et al., 2022, Sarrou et al., 2019).

### 3.1.2 Aquaponic

Aquaponic is an innovative system, capable of guaranteeing high production and sustainable management of cultivation resources, against food insecurity, drought and soil fertility loss (FAO, 2016). Such potential is particularly crucial in African countries, where climate change and urbanization are aggravating already precarious food systems (Blekking et al., 2022). Some African countries are already applying aquaponic as a sustainable and circular solution to foster food accessibility and optimization of cultivation inputs such as water, fertilizers and soil. Among African countries, Egypt is the one with the highest number of publications on the topic (Obirikorang et al., 2021), as recirculation of water in aquaponic systems can ensure a reuse efficiency rate around 95% (Dalsgaard et al., 2013), with impacting consequences on water scarcity and groundwater preservation in such arid regions (El-Essawy et al., 2019).

In the present SLR, selected articles associated fish production with different hydroponic systems such as growing beds with expanded clay or lava rock (Asciuto et al., 2019), floating system with clay pebbles in net pots (Vlahos et al., 2019), or a mix of NFT, DWC and growing beds (Fernández-Cabanás et al., 2023) (**Table 4**). Although, aquaponic can be combined with different typologies of hydroponic, productive efficiency can widely change. A research developed in Egypt, compared the yield of two different hydroponic systems associated to aquaculture, namely deep-water culture (DWC) and sand-bed system, showing an increase of 30% of production in case of DWC (Salem, 2019).

Aquaponic production includes both fish and vegetables. The combination of fish-vegetable production demonstrated to produce 5 times more vegetables as compared to traditional on-soil cultivation, as well as 29% and 75% more fish as compared to aquaculture alone, with recirculating and static system respectively (Oladimeji et al., 2020).

In the present SLR, two aquaponic systems located in Mediterranean area (i.e., in Italy and Spain), with a cultivable area around 5 $m^2$ and a fish tank around 1 $m^3$, were respectively capable of producing 37 kg $year^{-1}$ of lettuce and 72 kg $year^{-1}$ of Tilapia (Asciuto et al., 2019); and 68 kg $year^{-1}$ of lettuce and 33 kg $year^{-1}$ of Tilapia (Fernández-Cabanás et al., 2023) (**Table 3**). The difference between productive capacities could be related to diverse factors, including environmental conditions, system management, or type of hydroponic cultivation system. However, the higher production of lettuce in Fernández-Cabanás et al. (2023), could be once again associated to the type of hydroponic system. Indeed, 68 kg $year^{-1}$ of lettuce production in Fernández-Cabanás et al. (2023) was achieved using a combination of cultivation systems, namely NFT, DWC and growing bed, while 37 kg $year^{-1}$ in Asciuto et al. (2019) was achieved using growing bed only.

In the framework of a current agriculture affected by increasing saline soils, limited freshwater and more than 50% of groundwater containing saline water, the adoption of brackish water in aquaponic systems may represent an interesting alternative to increase productions sustainability and circularity (Kotzen and Appelbaum, 2010; Boxman, 2015). The present SLR shows an example of feasible application of brackish water for safe and high nutritional value production of Rock Samphire and Sea Bream in Mediterranean context (Vlahos et al., 2019) (**Table 4**).

**Table 4: Food production in aquaponic systems of Mediterranean area**

| Article | Country | Type of cultivation system | Species | Productive capacity |
|---|---|---|---|---|
| Asciuto et al. (2019) | Italy | Grow beds with expanded clay and lava rock | Lettuce and Nile tilapia | 7 kg $m^{-2}$ (lettuce) and 72 kg $m^{-3}$ (Nile tilapia) |
| Vlahos et al. (2019) | Greece | Floating system with clay pebbles in net pots | Rock samphire and Sea Bream | 2 g $plant^{-1}$ with 8ppt of water salinity and 0.5 g $plant^{-1}$ with 20 ppt water salinity (Rock samphire) |
| Fernández-Cabanás et al. (2023) | Spain | NFT, DWC and growing beds | Basil, stevia, chard, broccoli, Chinese cabbage, lettuce, tomato, red pepper, pumpkin, eggplant, cucumber, pepper, onion, cauliflower, cabbage, zucchini, potato and Red hybrid tilapia | 39 kg $m^{-2}$ -$year^{-1}$ (mean of total crops) and 34 kg $m^{-3}$ (Red hybrid tilapia) |

### 3.1.3 Vermiculture

Vermiculture is a circular agricultural practice based on the recycle of different types of organic wastes from farms, industry or household (Garg et al., 2006). The two main outputs of vermiculture are vermicompost and worms (i.e., *Eisenia fetida*). Both products could have a market value and productive application, as vermicompost can work as low-cost fertilizers, and worms can work as animal feed (e.g., poultry). In particular, vermicompost may represents an interesting economic source or saving for low-income realities, where access to mineral fertilizers could represent an excessive cost (Nova Pinedo et al., 2019) and selling of vermicompost self-production could become a small income source.

Vermicompost is an organic fertilizer rich in nutrients, which also has an important soil conditioner function for amelioration of arid or semi-arid soils (Kayabasi and Yilmaz, 2021). In the present SLR, the use of vermicompost as an organic fertilizer for open field Leguminosae production under Mediterranean arid and semi-arid condition, showed great effects on yield especially when combined with microbial inoculation (Ugar, 2021; Yürürdurmaz, 2022) (**Table 5**). Beside Leguminosae species, vermicompost could be used for cultivation of niche products with applications in cosmetic and pharmaceutical industry, which may represent an interesting economic opportunity for developing Mediterranean countries. In particular, greenhouse *Aloe vera* production and biological conditions of soil seemed to benefit from a combination of cattle manure vermicompost and vermiwash (liquid part of vermicomposting) (Tavali and Ok, 2022) (**Table 5**).

**Table 5: Vermicompost productive capacity in arid and semi-arid conditions of Mediterranean**

| Article | Country | Mean environmental conditions | Species | Productive capacity |
|---|---|---|---|---|
| Uçar (2021) | Turkey | 20°C, 44% RH | *Vicia faba* | 1907 kg $ha^{-1}$ of grains (vermicompost + *Rhizobium leguminosarum*, dose of 800 kg ha-1) |
| Tavali and Ok (2022) | Turkey | 26°C, 62% RH | *Aloe vera* | 638 g of fresh gel (cattle manure heated vermicompost + vermiwash, dose of 30 tons $ha^{-1}$) |
| Yürürdurmaz et al. (2022) | Turkey | 25°C, 52% RH | *Vigna unguiculata* | 4128 kg $ha^{-1}$ of grains (vermicompost + Rhizobium leguminosarum, dose of 800 kg $ha^{-1}$) |

Note: °C = degree Celsius; RH = relative humidity.

### 3.1.4 Insect farming

Production of insects for human and animal consumption has been gaining attention as an alternative protein source from livestock. Indeed, insects' protein content ranges from 350 to 700 g/kg, with a quality comparable to beef and fish (Straub et al., 2019). The identified eatable insect species are around 2000 (Jongema, 2015). Insects can convert food in a very efficient way, furthermore requiring very low land and water consumption with a consequent important impact on GHG emissions.

The present SLR showed that the most recent research in Mediterranean countries has been concentrated in Greece, for the production of Tenebrio Molitor (Rumbos et al., 2021; Rumbos et al., 2022; Adamaki-Sotiraki et al., 2022a; Adamaki-Sotiraki et al., 2022b). This species, also named yellow mealworm, is qualified for industrial production and has been recognized as an ingredient for fish feeding and safe for human consumption by the European Union (EU) (Turck et al., 2021). As in the case of livestock, research is focusing on different strains to ameliorate mass-rearing production. A first article on evaluation of different strains, showed that strains from Mediterranean countries (i.e., Spain, Greece, Italy, Turkey) present better egg hatching and number as compared to strains form northern latitude (i.e., Germany) (Adamaki-Sotiraki et al., 2022a). On the other hand, a second research highlighted that a German strain had the highest final larval weight at harvest as compared to Mediterranean once (Rumbos et al., 2021). Finally, a third study on strains response to dry condition (26 °C, 50% RH), showed no difference in case of final larval weight and survival rate among strains (Adamaki-Sotiraki et al., 2022a).

The type of diet could also affect larvae weight. A research focused on use of different agricultural by-products from Mediterranean context for larvae feeding, showed that use of barley and oak by-products can give good performances as compared to traditional wheat bran diet on terms of larval weight gain (Rumbos et al., 2022).

### 3.1.5 Rooftop agriculture

Rooftop agriculture, applied both as open-air and in greenhouses, has been identified as a sustainable cultivation method for urban context, benefiting the cities at environmental (e.g., heat island effect reduction, stormwater management), social (e.g., social integration of disadvantaged people) and economic (e.g., creation of job opportunities) level (Appolloni et al., 2021).

In the present SLR, the totality of identify studies in the Mediterranean area were located in Spain. Most of such researches have been performed in an integrated rooftop greenhouse on top of the ICTA Research Center of the Autonomous University of Barcelona (Parada et al., 2021a; Parada et al., 2021b; Appolloni et al., 2022) (**Table 6**). Such infrastructure is a unique example of sustainable and circular building integrated agriculture. Indeed, the concept beyond the infrastructure is to combine the two metabolisms of the building and of the greenhouse, exchanging gases (i.e., $CO_2$), energy (i.e., heat) and water (i.e., rainwater), to save resources and reduce GHG emissions (Sanyé-Mengual et al., 2014). The above-mentioned articles analyzed different ways to achieve good productive capacity while increasing circularity and sustainability in the integrated rooftop greenhouse. Parada et al. (2021a; 2021b) evaluated different solutions to optimize crop production in rooftop greenhouse with limited water availability. In the first study (Parada et al., 2021a), the research considered different type of substrates (i.e., compost, coir, perlite and mixture of compost and perlite) for lettuce production in drought condition. Results showed that organic substrates (alone or in mixture) can give similar or higher productions than perlite, therefore demonstrating feasibility for substituting this highly impacting substrate. In a second research, Parada et al. (2021b) evaluated the effects on yield of different irrigation regimes: recirculation of drained water, recirculation of drained water + 15% of fresh water, and open management. The results reported similar yields (17.9, 16.8 and 16.2 kg $m^{-2}$, respectively), highlighting the potentiality of water recirculation.

In rooftop greenhouse context, yield could be limited by low light transmission due to building structural items and low transmissivity of ageing fireproof covering materials (i.e., polycarbonate). Use of supplemental LED light demonstrated a capability to increase productivity by 17% as compared to natural light alone, although energetic costs that are still making the practice not economically valuable (Appolloni et al., 2022). Use of renewable and building-integrated energy sources, such as solar panels, could represent a good alternative to reduce electricity costs and environmental impact of supplemental light application. Such panels are often applied on top of rooftops, therefore risking to compete with rooftop cultivation. However, a research by Carreño-Ortega et al. (2021) located in Almeria, Spain, demonstrated that mini-PV modules with a scattered shadow could produce lettuce almost 90% bigger as compared to full sun (**Table 4**). This result demonstrates interesting potentialities for Mediterranean area, especially in case of areas with intense sun radiation.

An important role of rooftop agriculture is also associated to food security and self-sufficiency in cities, especially in case of families in less advantaged conditions (Chowdhury et al., 2020). The article by Boneta et al. (2019) investigated such potentiality for the city of Barcelona. The soil-less polyculture rooftop garden of 18 $m^2$ demonstrated of being capable to produce 10.6 kg $m^2$ in one year, meaning that 5.3 $m^2$ would be enough to cover the vegetables requirement for one citizen (**Table 6**). Furthermore, water consumption resulted around 3.7 L $m^{-2}$ $d^{-1}$, while wasted biomass was around 3.3 kg $m^{-2}$ (Boneta et al., 2019).

**Table 6: Productive capacity of rooftop agriculture systems**

| Article | Country | Type of rooftop cultivation system | Species | Productive capacity |
|---|---|---|---|---|
| Boneta et al. (2019) | Spain | Open-air garden | Lettuce, Chard, Spinach, Tomato, Zucchini, Endive, Cabbage, Green pea, Strawberry, Arugula, Pepper, Eggplant, Broccoli, Celery, Melon, Cucumber, Broad bean, Cauliflower, Bean, Thistle, Artichokes | 10.6 kg $m^{-2}$ $year^{-1}$ (mean of total crops) |
| Parada et al. (2021a) | Spain | Integrated rooftop greenhouse | Lettuce | 439, 416, 426 and 441 g $plant^{-1}$ (perlite, coir, compost and mixture of compost and perlite 1:1, respectively) |
| Parada et al. (2021b) | Spain | Integrated rooftop greenhouse | Tomato | 17.9, 16.8 and 16.2 kg $m^{-2}$ (recirculation of drained water, recirculation of drained water + 15% of fresh water and open management, respectively) |
| Carreño-Ortega et al. (2021) | Spain | Open-air garden | Lettuce | 89, 140 and 75 g $plant^{-1}$ (mini-photovoltaic concentrated shadow, scattered shadow and full sun, respectively) |
| Appolloni et al. (2022) | Spain | Integrated rooftop greenhouse | Tomato | 3.6 and 4.4 kg $plant^{-1}$ (natural light and LED light treatments, respectively) |

### 3.1.6 Saline agriculture

Arid and semi-arid regions of Mediterranean area are getting increasingly vulnerable due to fresh water scarcity for food and fodder production (Van Dijk et al., 2021). Indeed, climate change consequences related to reduction of precipitations and increase of droughts periods are causing a reduction of water quality and increasing salinity of groundwater reservoirs (Lyra et al., 2022). In this framework, the use of saline water is the only practicable solution to guarantee resilience of arid ecosystems (Yu et al., 2021). Therefore, the identification and evaluation of halophytes species to be used for human or animal nutrition is fundamental (Panta et al., 2014) (Table 7 ).

Beside productive capacity, the cultivation of crops and forages with saline water should also consider imbalances in mineral composition and eventual toxicity accumulation (Díaz and Grattan, 2009). Alfa alfa, a fundamental forage plant in arid and semi-arid regions of the world, is considered moderately sensitive to salinity, although some varieties have been confirmed to resist better to salinity (Djilianov et al., 2003; Purìtnam et al., 2017). A research by Diaz et al. (2018) revealed that although the yield of *Alfa alfa* decreased with an increasing salinity, the tolerance resulted higher than what previously reported in literature for this species, furthermore being categorized as "supreme" quality from a nutritional standpoint. However, the content of some toxic elements (SKB) was near or above the tolerable levels, suggesting the necessity to combine the product with other forages for long term consumption. Beside traditional forages, the Mediterranean saltbush is another interesting halophyte fodder typical of arid and semi-arid areas and with a high protein content. In the present SLR, Alotibi et al. (2023) observed that Mediterranean saltbush production in Egypt could be affected by seasonal changes, reducing productivity by 50%, as well as nutrients content.

Animal feeding is not the only purpose of halophytes. Indeed, given high nutritional values of some species, consumption could also be particularly useful for human diet. Plants of *Salicornia* genus have been identified among various halophytes as those more nutritionally and economically interesting (Ventura and Sagi, 2013). These observations and potentiality in Arid and Semi-Arid Mediterranean countries were also corroborated by Lyra at al. (2022), founding out an effect of salinity on ions accumulation, fatty acids and amino acids.

**Table 7: Productive capacity of saline agriculture**

| Article | Country | Mean environmental conditions | Species | Productive capacity |
|---|---|---|---|---|
| Diaz et al. (2018) | Spain | 21.5°C, 68% RH | Alfa alfa | 6, 5.5, 4.8, 4.1 and 3.4 g $m^{-2}$ (400, 2500, 5000, 7500 and 10000 µS $cm^{-1}$, respectively) |
| Lyra et al. (2022) | Egypt | 25°C, 39% RH | Salicornia | 6.5 kg $m^{-2}$ (green biomass), 79 g $m^{-2}$ (seeds) |
| Alotibi et al. (2023) | Egypt | 25°C, 47% RH | Mediterranean saltbush (*Atriplex halimus*) | 8.5 tons $ha^{-1}$ |

Note: °C T = degree Celsius; RH = relative humidity

## 3.2 Waste

### 3.2.1 Hydroponic

Although it was shown that hydroponic system is more resource efficient than on-soil agriculture, they have to cope with a large environmental burden associated to the management of mineral fertilizers, the use of growing media, and also to the higher energy consumption for satisfying the crop thermal requirements in greenhouses. At the same time, hydroponic facilities are producing a large amount of by-product, such as the non-commercial biomass of the crop at the end of the growing cycle. For instance, Gioulounta et al. (2023) valorized the massive amount of tomato and cucumber biomass residues grown in greenhouse producing biomethane. However, data related to the amount of energy used for producing biomethane are not reported, limiting the possibility to perform an energy balance to assess the economic and environmental benefit. Also, the increasing risk of drought in Mediterranean is leading authors on finding alternative sources of water for satisfying crop requirements. Spain is actively promoting the research on the use of desallinisators for treating seawater where previous literature was previously examined (Martinez-Mate et al. 2018; Martinez-Granado et al. 2022). The adoption of desallinisators is not exempt from the of waste disposal generation, commonly named rejected brine, which is often discharged into the sea threatening flora and fauna. Since rejected brine concentrates different mineral nutrients, it has been integrated as part of the nutrient solution of a hydroponic tomato crop (Jiménez-Arias et al. 2020). Though the use of rejected brine increase the salinity of the nutrient solution leading to a reduction of the yield, it allows to save up to 20% of the cost associated to the nutrient solution and to an improvement of the quality of the fruits. On the other hand, the extensive production of olive oil in Mediterranean countries generate a high amount of olive mill wastewater (OMW). The presence of a high concentration of phenolic compounds in the OMW result in phytotoxic and antimicrobial properties, which limits its dumping into the soil. However, OMW can be bio-detoxified by using yeast and bacterial reducing the phytotoxic properties, and potentially it can be used as raw material for preparing nutrient solution for hydroponic crops (Ramires et al. 2020).

### 3.2.2 Aquaponic

Aquaponic has already been cited as a cultivation system that perfectly aligns with the concepts of circular production and waste reuse. Indeed, the system is characterized by the integration of two cultivations systems reciprocally benefiting from recirculation of nutrients and water among them. Specifically, the two systems are represented by a Recirculating Aquaculture System (RAS) and a hydroponic system for vegetables cultivation. The wastes and uneaten food by fishes are used as fertilizers for plants cultivation after the action of nitrifying bacteria making nutrients available. On the other side, plants act as water depurators, recycled in fish tanks (Krastanova et al., 2022).

The present SLR identified different researches applying this circular system in Mediterranean countries (Asciuto et al., 2019; El-Essawy et al., 2019; Fernández-Cabanás et al., 2023). Beside fish waste reuse for plants cultivation, aquaponic sustainability could be further improved by reusing wastewater sources. A research by Cherif et al. (2023) investigated new technologies for tertiary wastewater reuse in aquaponic systems. The research showed that a treatment combining a moving bed biofilm reactor, a wetland with two types of plants (*Juncus maritimus* and *Commun phragmitis*), sand, activated carbon filters and a nanofiltration can significantly ameliorate water quality for aquaponic systems and helped to almost duplicate fish weight.

### 3.2.3 Vermiculture

Vermicomposting is a process of bio-oxidation and stabilization of organic wastes thanks to the coordinated biological activity of earthworms and microorganisms in aerobic conditions (Adhikary, 2012). Many typologies of wastes can be used to obtain vermicompost, from paper residues to municipal sewage sludges (Gajalakshmi and Abbasi, 2004; Suthar, 2009). Such reuse of organic wastes is of fundamental importance for reducing environmental impact, not only giving an alternative to use of chemical fertilizers, but also giving a new life to potentially environmentally harmful wastes.

The aquaculture sludge is a by-product of fish production. With the intensification of aquaculture systems, high amounts of such solid waste have been produced determining a potential negative impact on environment due to the high concentrations of phosphorus and nitrate. A research set in Algeria evaluated the effect of vermicomposting of aquaculture sludge for stabilization and safety, as well as its effect for plant cultivation (Belmeskine et al., 2023). The results showed that vermicomposting can ensure good hygiene and safety standards, as well as increase of *Phaseolus vulgaris* vegetative parameters.

Local availability of wastes is another fundamental aspect to consider to reduce the environmental impact of vermicompost. Local industrial wastes can also represent an opportunity, as in the case of by-products of beer industry, such as spent grains. A research in Egypt showed that vermicompost from beer industry spent grains can increased wheat fresh weight and soil micronutrients as compared to a control without fertilizer and a NPK fertilization, highlighting the feasibility of such by-products (Rashad et al., 2023).

### 3.2.4 Insect farming

Sustainability of insects' production is mostly affected by feed cost (Roffeis et al., 2018). Accordingly, research is focusing on the use of low-cost organic wastes to integrate insects' diet (Gasco et al., 2020). Agricultural wastes represent a great opportunity for sector circularity, especially in developing countries (Sheikh et al., 2022). The use of organic agricultural by-products as insect feed has been studied for many species: *Hermetia illucens*, *Ruspolia differens, Alphitobius diaperinus, Zophobas morio* and *Tenebrio molitor* (Van Broekhoven et al., 2015; Bava et al., 2019; Sorjonen et al., 2020; Gianotten et al., 2020). Among above mentioned species, *Tenebrio molitor* is one of the most common for food and feed production. Its traditional diet is base bran added with proteins such as yeast, soy, casein etc. Many studies have evaluated the use of organic wastes to reduce diet cost (e.g., cattle and horse manure, beet molasses, bread and cookies remains, remains from olive oil production) (Ooninx et al., 2015; Van Broekhoven et al., 2015; Hasanyi et al., 2020; Ruschioni et al., 2020). A research identified in the present SLR, investigated the viability of different agricultural wastes locally available in Mediterranean context (i.e. Greece) for costs reduction of *Tenebrio molitor* diet (Rumbos et al., 2022). The results showed that the best economic conversion ratio (ECR) was obtained with oat diet (194 € ton$^{-1}$), given the low price (120 € ton$^{-1}$) and efficient conversion by the insect. Table 8 reports a summary of the energetic values, prices of the by-products used in the Rumbos et al. (2022).

**Table 8: Prices, energetic values and economic conversion rate (ECR) of agricultural by-products**

| Article | Country | Agricultural by-product | Price (€ $ton^{-1}$) | Energy (kJ $g^{-1}$) | ECR (€ ton $larvae^{-1}$) |
|---|---|---|---|---|---|
| Rumbos et al. (2022) | Greece | Wheat bran (control) | 170 | 16.7 | 396 |
| | | Sugar beet pulp | 210 | 17.3 | 1017 |
| | | Cotton cake | 240 | 18.5 | 952 |
| | | Cotton seed meal | 350 | 20 | 1619 |
| | | Sunflower meal | 220 | 17.1 | 611 |
| | | Barley by-product (class I) | 100 | 14.5 | 597 |
| | | Barley by-product (class II) | 140 | 16.2 | 261 |
| | | Oat | 120 | 16.9 | 193 |
| | | Pea by-product (class I) | 100 | 10.9 | 779 |
| | | Pea by-product (class II) | 220 | 16.3 | 4363 |
| | | Vetch by-product (class I) | 100 | 15.1 | 416 |
| | | Vetch by-product (class II) | 270 | 14.7 | 3705 |
| | | Yeast (control) | 8000 | 19.9 | - |

### 3.2.5 Rooftop agriculture

When talking about circularity of agricultural systems, reuse of organic wastes is not the only aspect to consider. In an integrated rooftop greenhouse of Mediterranean context, wasted airflows can be exchanged between both infrastructures (i.e., greenhouse and building) increasing their energy efficiency. As reported by Munoz-Liesa et al. (2022), the thermal energy that can be recirculated from the greenhouse to the building is around 205 kWh $m^2$ $y^{-1}$, while the thermal energy from the building capable of heating and cooling the greenhouse is around 198 kWh $m^2$ $y^{-1}$, with consequent significant effects on carbon emissions.

Beside wasted energy, a rooftop greenhouse can also increase its circularity and sustainability by recirculating wasted water and nutrients. A life cycle assessment on bean production in a Mediterranean rooftop greenhouse showed that 40% of water and 35-54% of nutrients could be saved daily by using a closed-loop irrigation (Rufí-Salís et al., 2020a). Nutrient's recirculation can reduce eutrophication risks and save more $CO_2$ as compared to other nutrients recovery systems (i.e., chemical precipitation, membrane filtration) (Rufí-Salís et al., 2021). Although the higher complexity of infrastructures for recirculating systems could have a major impact in terms of global warming and fossil fuels request, different strategy could be applied to reduce such negative effects including recycle of construction materials (Rufí-Salís et al., 2020a; Rufí-Salís et al., 2020b).

## 3.3 Energy efficiency, renewable energy sources and transition

### 3.3.1 Hydroponic

The use of renewable energy resources like solar panels and the use of automatized controlled systems for hydroponic plant cultivation leads to the creation of a more energy-efficient and eco-friendly cultivation systems. This has significant benefits for society and environment to foster a greener tomorrow. Automatized controlled systems can optimize irrigation basing on crop growth standard parameters, therefore optimizing energy consumption. When values deviate from the acceptable range, the control system takes action to stabilize conductivity and pH levels using sensors. Maintaining these parameters is crucial to prevent diseases and give an adequate and optimized nutrition. Incorrect pH levels can hinder growth, lead to toxicity, fungal infections, and poor nutrient absorption, ultimately resulting in plant deterioration. This control and automation system not only monitors the pH, conductivity and temperature in nutrient solutions, but also continuously records these values, creating a valuable dataset for improving future production quality. The system's design also reduces the need for constant user intervention. It enhances production quality and profitability for the producer. Automatized controlled systems can be sourced by solar-power. It is possible to use a 12Watt (W) solar panel, a solar charger controller, and a 12V lead acid rechargeable battery to power an hydroponic system. The monitoring system can be driven by an Arduino Uno microcontroller, tracking temperature, water level, and pH, and displaying the data on an LCD screen. Then, the system's effectiveness is validated through data analysis. Controlled environment hydroponic systems typically consume substantial electricity for various purposes, contributing significantly to carbon footprint. However, if powered exclusively by renewable energy sources integrated in the farm, these systems can potentially have a lower carbon footprint than traditional supply chains.

In the present SLR, selected articles emphasized the importance of aquaponic systems and renewable energy sources in the field of aquaponic. Aquaponic system can be an ideal solution for the cultivation of species such as water spinach (Ipomoea aquatica), Nile tilapia fish (Oreochromis niloticus), and lettuce (Lactuca sativa), optimizing waste management and water use (Nagayo et al., 2017). Aquaponic has been proven to perform consistently well during both the winter and summer seasons. Supplemental lighting treatment may be fundamental to increase productivity during winter time in some Mediterranean areas (e.g., Italy, Spain). However, Vanacore et al., (2022) found out that electricity used for LED light could determine a much higher environmental impact of the aquaponic system. Mohamad et al. (2013) investigated the use of solar powered control solar pumps to reduce the energy impact in aquaponic systems, highlighting the possibility to integrate such systems to enhance aquaponic sustainability.

### 3.3.2 Rooftop agriculture

Application of solar energy panels on urban rooftops could compete with food production. A cost-benefit analysis demonstrated that food production in a rooftop greenhouse is more beneficial than energy generation, for both the owner of the system and the local community (Benis et al., 2018). However, in some type of systems, vegetables and energy production on rooftop can be successfully integrated, creating an optimal exploitation of urban unused surfaces (Carreño-Ortega et al., 2021).

## 3.4 Ecosystem services and carbon footprint

Ecosystem services are goods and services or benefits that mankind receives from the natural environment such as clean water, air and food, amenity and recreational values. The concept of ecosystem services has now gained widespread acceptance through the Millennium Ecosystem Assessment Program (Millennium Ecosystem Assessment Program, 2005). A number of approaches have been developed in the past to categorize ecosystems services. The Millennium Ecosystems Assessment distinguished four groups of ecosystem services: (1) provisioning services referring to products obtained from ecosystems such as supply of food, water, fiber, wood and fuels; (2) regulating services referring to benefits obtained from the regulation of ecosystem process (e.g., the regulation of air quality and soil fertility, control of floods or crop pollination); (3) supporting services which are necessary for the production of all other ecosystem services (e.g., by providing plants and animals with living spaces, allowing for diversity of species and maintaining genetic diversity); and (4) cultural services referring to non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences (FAO, 2015). Frontier agricultural technologies, e.g. aquaponic and hydroponic farming provide ecosystem services such as improvements to air and water quality, landscaping, and thermal comfort, energy conservation or carbon sequestration (FAO, 2015; Paudel and States, 2023). Other types of frontier agricultural technologies, i.e., vermicomposting, have also been shown to yield several ecosystem benefits including enhancing soil health and treatment of hazardous substances (FAO, 2015).

### 3.4.1 Hydroponic

Greenhouse cultivation in the Mediterranean region has undoubtedly enhanced economic growth and has generated social benefits by making an efficient use of natural resources (Verner, 2017). However, these production systems also caused undesirable environmental impacts (IPCC, 2007, Valin et al., 2014). A rising metropolitan areas takes 70-80% of energy consumption and energy related $CO_2$ emissions (Gilles et al., 2021) aggravating the existing challenge. In recent years, integrating the water, energy, food and ecosystem has been seen as a promising innovative solution to tackle the environmental burden and to make agricultural practices sustainable (European Commission, 2020). To reduce the magnitude of the carbon footprint index, innovative food production systems such as soilless production and climate smart technologies are being developed (Verner, 2017). Urban agriculture also reduces the “geographical” food value chain significantly and thus the environmental pressure (Llorach-Massana et al., 2017).

Consistent with the findings by Giordani et al. 2022 and (Atzori et al. 2021), Chatzigeorgiou et al. (2022) compared the different substrates and their environmental impacts and indicated that impact on the environment significantly varies depending on the type of substrates applied to the hydroponic systems and revealed that 1.7 perlite treatment contributes the lowest product carbon footprint compared to the other substrates.

### 3.4.2 Vermiculture

The rapid increase in population led to significant increase in waste generation, which has a detrimental impact on the environment. Consequently, waste management is imperative to bring sustainable development. For instance, wastes such as agricultural waste can be recycled back into the soil as organic waste. However, wastes from industries may contain hazardous substances that cannot be recycled (Asokan et al., 2004). Thus, improper waste disposal of hazardous or non-hazardous waste causes serious environmental problems. One of the waste management strategies is vermicomposting. Vermicomposting is a process of bio-oxidation and stabilization of organic wastes (Adhikary, 2012). Vermicomposting provides a natural fertilizer for agricultural use and improves soil health and thus preventing soil degradation and improve bio-diversity (Varma and Kalamdhad, 2014).

Vermicomposting may have different roles. For instance, the application of vermicompost tea offers and eco-friendly alternative to substitute synthetic fertilizers to enhance plant growth. Additionally, vermicompost tea can serve as a natural pesticide or fungicide, safeguarding plants from diseases and reducing the reliance on chemical fungicides and pesticides. This contributes further to alleviating the environmental pressures associated with extensive food production. For instance, heavy metals such as copper are commonly used as a fungicidal treatment for olive leaf spot. However, copper is highly toxic to useful microorganisms in the soil and plant products if present in excess concentration (Flemming and Trevors, 1989; Maliszewska et al., 1985). In our SLR analysis, research by Kir et al. (2022) in Türkiye compared the efficacy of soil conditioner (vermicompost tea), fertilizer (Potassioum silicate), and biological control agents such as potential substitutes for copper. The study found that vermicompost, which is easily accessible, have potential for use in organic olive production to replace copper in mitigating leaf spots, implying that the alternative helps to reduce copper application and in turn decrease copper accumulation in soil, fruits and leaves.

### 3.4.3 Rooftop agriculture

Greenhouse agricultural production is an important source of food for urban areas with a lesser environmental impact due to shorter value chains and the possibility of integrating with buildings as well as applying circularity (Platis et al., 2021). Despite these advantages, greenhouse production can also contribute to a significant amount of greenhouse gasses as it is an energy-intensive sector. Integrating greenhouses on top of buildings has recently been seen as an innovative way to produce locally, increase energy savings and decrease carbon emissions by connecting the greenhouse and building metabolisms (Boneta et al., 2019; Rufí-Salís et al., 2021). Integrated rooftop agriculture can act as a sink for the building's low grade waste heat (Muñoz-Liesa et al., 2022; Rufí-Salís et al., 2021), and solar collector (Muñoz-Liesa et al., 2022; Zambrano-Prado et al., 2021).

The implementation of innovative production systems like rooftop hydroponics, to produce mainly leafy vegetables and fruits, are considered a sustainable approach that can substantially alleviate environmental stress and conserve water resources. The environmental impact or carbon footprint of these practices varies depending on type of crop, season, infrastructure used and the type of media. A study by Rufí-Salís et al. (2020a) in Spain compared the environmental impact of 25 different types of crops cultivated using rooftop hydroponics over the course of 4 years revealed that out of all the crops considered spinach and arugula showed the highest environmental impacts. On the other hand, tomato cycles found to be the best alternative for environmental impact considering it high yield (Boneta et al., 2019) (Table 9).

Other factors that determine the extent of environmental impacts/carbon footprint of the different cultivation systems is seasonality. The majority of evidence revealed that spring crops exert less impact on the environment compared with colder winter season (Ceccanti et al. 2022; M. Rufí-Salís et al. 2020). According to Rufí-Salís et al. (2020), diversifying and combining different cultivation systems leads to better environmental performance. The largest source of greenhouse emissions, however, come from the greenhouse structure itself (Rufí-Salís et al., 2020a), followed by fertigation (Boneta et al., 2019; Munz et al., 2008; Romero-Gámez and Suárez-Rey, 2020). Fertigation is a method of fertilizer application in which fertilizer is incorporated within the irrigation water by the drip system. Fertigation is an important source of nitrogen and phosphorus emissions that cause freshwater eutrophication (Boneta et al., 2019; Munz et al., 2008).

On the other hand, given the ongoing extreme pressure exerted on the water and energy sector and the limited availability of arable land, circular economy is believed to be an innovative way to enhance resource use efficiency and economic growth (European Commission, 2020). Several studies assessed the possibility of applying circularity approach in rooftop agriculture enhancing sustainability of the production system (European Commission, 2020). Rufí-Salís et al. (2021) provided a comprehensive analysis on the performance of applying circular strategies in urban agricultural systems by comparing 13 different cultivation scenarios in the Mediterranean areas. The study compared different combinations of innovative strategies with a baseline scenario where a hydroponic rooftop greenhouse was irrigated with rainwater (80%) and used inorganic fertilizer. Their findings revealed the potential benefits of applying circularity in rooftop agriculture at different degrees on the different scenarios for Spain. Moreover, the study revealed that a scenario combining different strategies showed great impact reduction compared to the baseline scenario in all environmental indicators. However, it is also shown that the circularity has trade-offs in terms environmental performance that can be improved by adopting different combinations of innovative production systems.

**Table 9 Environmental impact performance of Rooftop greenhouse system, and vermicompost**

| Article | Country | System | Impact on Carbon footprint Ecosystem Service |
|---|---|---|---|
| Kir et al. (2022) | Türkiye | Vermicompost | • Substitute heavy metals |
| Muñoz-Liesa et al. (2022) | Spain | Integrated Rooftop Greenhouse | • Reduced $CO_2$ emissions;<br>• Energy recirculation saved 8% of the building yearly energy consumption<br>• Healthy food, improved soil quality |
| Rufí-Salís et al. (2020°) | Spain | Integrated Rooftop Greenhouse | • Tomato is the crop contributing the least to environmental burden; spring tomato have highest yield with lowest environmental impact |
| Rufí-Salís et al. (2020b) | Spain | Open hydroponic | • less impact on global warming<br>• Extra infrastructure not needed |
| | | Closed Hydroponic | Compared to the open system<br>• 35-45 % of nutrients saved<br>• 40% irrigation water saved<br>• Higher yield<br>Trade-off may cause fossil resource scarcity; extra infrastructure contributes to global warming |
| Romero et al. (2020) | Spain | Hydroponic | • The most innovative hydroponic system (macro-tunnel soilless integrated) offered less environmental impact<br>• Closed field strawberry environmentally friendly than the open<br>• Fertilizers were the top categories with the most environmental impact |
| Maaoui et al. (2020) | Tunisia | Hydroponic | • Fertilizers and energy sub-systems are the most contributing in the majority of the environmental impacts<br>• Recycling waste reduced carbon footprint significantly |

Substrates are also important components of hydroponic production with different water saving efficiency and varying environmental impact (Atzori et al., 2021). The main substrates that are considered environmentally friendly and yield enhancing are organic substrates mainly made from local materials. Organic substrates such as compost are also proved to increase resilience of crop against drought and water shortage. In our SLR, Parada et al. (2021) compared the production resilience impact of organic substrates made from local materials in urban integrated rooftop agriculture to temporary drought in Spain.

### 3.4.4 Saline agriculture

Salinity generally has negative effects on soil productivity that lead to low crop yield, threatening food production and food security. Moreover, salinity adversely affects ecological diversity. The cultivation of salt tolerant crops is, thus, a practicable solution to improve soil quality, conserve the ecosystem and increase productivity. The Mediterranean area has high biodiversity in terms of endemic halophytic vegetation providing an alternative pool of potential new agricultural products to be cultivated in adverse environmental conditions (Altay and Ozturk, 2012). The ecological benefits of salt tolerant crops in biosaline agroecosystems such as halophytes were examined by Duarte and Caçador (2021). This article identified different applications of these species as food, forage and source of nutraceutical molecules, ornamental purposes as week as soil health and improved bio-diversity.

It is also emerged that saline agriculture can be integrated with soilless production systems, particularly aquaponics that could be successfully implemented to meet food demand while keeping the environmental pressure lower (Ben Hamed et al., 2021; Martinez-Mate et al., 2018; Martin-Gorriz et al., 2021). A Mediterranean based study by Ben Hamed et al. (2021) found that integrating salt tolerant crops with aquaponics improves agro-biodiversity, increase productivity and improve food security. These findings show the possibility of improving farming systems in the salt affected Mediterranean areas through the use of innovative practices such as the use halophytes combined with aquaponic and of desalinated seawater. The use of desalinated water also helps reduce the over-exploitation of ground water if combined with clean energy (Martin-Gorriz et al., 2021).

## 3.5 Business, social and technical readiness level

In this section, we will assess the findings of the SLR on technical, social and business readiness levels, viability, operational costs, labor requirements, yield and market integrations of climate smart and water saving frontier technologies. Readiness levels measure the maturity of new practices, products or services.

Technical readiness level (TRL) measures the technical maturity level of an innovation or product ranges from 1 to 9 where 9 stands for the highest-level maturity (i.e., the product general availability in the market), see also Annex I. The current technology readiness levels (TRLs) for different small- and medium-scale hydroponics, aquaponics, insect farming, and vermiculture/vermicomposting are below or at TRL 3-5 (Benjamin et al., 2021; Verner et al., 2021).

Business readiness level (BRL) on the other hand measures the business maturity level providing useful information regarding commercial and relationship with consumers. BRLs are also measured on a scale from 1-9, being 9 the most advanced one. In this way, BRL1-BRL3 focus on technical feasibility, BRL4-BRL6 on market segmentation and strategic positioning choices, and finally BRL7-BRL9 is about market launch. The popular product-market fit is achieved at BRL8 while the business model- market fit is achieved at BRL9 (see Annex II).

Societal Readiness Level (SRL) is a way of assessing the level of societal adaptation of, for instance, a particular social project, a technology, a product, a process, an intervention, or an innovation (whether social or technical) to be integrated into society. If the societal readiness for the social or technical solution is expected to be low, suggestions for a realistic transition towards societal adaptation are required (see Annex III).

### 3.5.1 Hydroponic

Currently, hydroponics is mainly used to grow leafy vegetables, tomatoes, cucumbers, peppers, herbs, and several other crops (Spensley et al., 1978). Hydroponic systems use approximately 80-99% less water than open field agriculture. The use of advanced hydroponic systems that use less water than simplified hydroponics is becoming common across diverse climates and agro-ecological zones, including arid areas (Heredia, 2014). In terms of costs and labor requirements hydroponics requires higher startup cost (Verner, 2017). A hydroponic greenhouse establishment can cost anywhere from 2 to 20 times more than the soil cultivation system (Mathias, 2014). However, some of the costs of a hydroponic system can be compensated due to the system's efficiency in the use of other operational costs such as labor, water, fertilizers and chemicals (Verner, 2017). The use of local materials are shown to solve the high startup costs of frontier technologies (Benjamin et al., 2020). Studies also show that the feasibility of hydroponic farming in general is heavily reliant on the agro-climatic characteristics of the farming locations (Barbosa et al., 2015).

Rapid urban expansion causes pressing concerns on the water, energy, and food security (WEE Nexus). Urban settlements consume about 70% of global resources and emit 70% of all greenhouse gases (European Investment Bank, 2018). This generates significant environmental, social and economic burdens. As a result of these pressing concerns, cities practice sustainable production and consumption. Moreover, food demand is expected to increase by 50% in 2050 that can only meet if cities manage resources through sustainable urban planning strategies as arable land and water are limited (International Renewabl energy Agency, 2015). Zambrano-Prado et al. (2021) in Spain (**Table 10**) assessed the technical feasibility of roofs for integrating urban agriculture, rainwater harvesting, and photovoltaic systems using various remote sensing for Spain. This study identified that 8% of the roof area in Barcelona to be feasible for tomato and lettuce production. The production of these two crops is also estimated to satisfy the 210% of average intake of tomatoes and the 21% average yearly consumption of lettuce (Zambrano-Prado et al., 2021).

The findings also show that **rainwater harvesting systems** could supply 94.26% of the water requirements for lettuce growing in an open-air system; in contrast, 53% of irrigation could be satisfied for tomato production in rooftop greenhouse systems. The results showed a potential for 80% of roof area to be used for rainwater harvesting systems, representing the average yearly water consumption of 44% of citizens for laundry, showering, toilet flushing, cleaning and irrigation uses. About 50% of the roofs are suitable for **photovoltaic panels**, representing an average energy consumption of 18% of citizens.

In another study in Egypt, Sadek et al. (2023) evaluated the environmental and technical impacts of smart systems (internet of things - IoT) on the greenhouse cultivation of Batavia Lettuce in Egypt. Consistent with other studies, their findings revealed that the innovative system can save about 80% of water, double the productivity per area and reduce the maturity days (45 days vs 75 days), save labor or fertilizer or pesticide use, compared with the traditional production system with soil.

**Table 10: Product quality and business feasibility/viability of hydroponics**

| Article | Country | System | Product quality and business feasibility/viability |
|---|---|---|---|
| Ceccanti et al. (2022) | Italy | Hydroponic | • Made possible to produce vine plants in two seasons<br>• Higher productivity compared to traditional farming |
| Chatzigeorgiou et al. (2022) | Greece | Hydroponic | • Highest yield achieved with pertile compared to soil cultivation and other substrates<br>• Hydroponic in general provide notably higher yield compared to soil |
| Boneta et al. (2019) | Spain | Rooftop Agriculture | • Out of 22 different crops produced over 2 years, were tomato, chard, lettuce, pepper and eggplant were the top 5 most productive crops |
| Giordani et al. (2022) | Italy | Hydroponic | • Substrate application in a hydroponic provided superior yield and quality of product |
| Sadek et al. (2023) | Egypt | Hydroponic, Aeroponics | • The use if Smart system doubled crop yield shortened growing season, saved labor and reduced the quantity of inputs used |

### 3.5.2 Aquaponic

Aquaponic is promoted as a means to make cities more sustainable (FAO, 2015), source of employment and entrepreneurship opportunities (Verner, 2017). Aquaponics is a relatively new innovation and thus its business viability is mostly inconclusive as a result of start-up costs and market risks.

A study by El-Essawy et al. (2019) (Table 11) in Egypt, evaluated the possibility of implementing aquaponics as an alternative to conventional agriculture. The study compared two pilot scale aquaponics systems (Deep water Culture system and Integrated Aqua-Vegaculture system), where crop quality (vitamins, heavy metals, and pesticides residues) of the two systems has been compared among each other, as well as to that of the commercially available organic food in supermarkets. The study revealed that both aquaponic systems produce high-quality safe organic food. In terms of economic feasibility, the study indicated that integrated Aqua-Vegaculture system is producing more crops with a wider variety of almost 20% less capital expenditure and operational expenditure costs.

A cost-benefit analysis on aquaponics project in Nigeria by Benjamin et al. (2020) shows that operating the aquaponics system is not feasible if the inputs are mainly sourced from abroad. According to El-Essawy et al. (2019), aquaponics entails relatively high capital and operational expenditure costs compared to conventional agriculture in the short term. However, on the long term, the study highlighted that aquaponics is more profitable while saving up to 85% of the water. In terms of the sensitivity if aquaponic production, though start-up costs are high for hydroponics medium scale producers are found to be less sensitive to changes in variable costs (Folorunso et al., 2023).

The socio-economic characteristics of climate smart and water saving technology adopters are also very crucial for targeting and support of the different innovators. In the present SLR, Suárez-Cáceres et al. (2022) identified the average aquaponic producer to be a middle-aged man, with a certain level of studies and a moderate household income. Suárez-Cáceres et al. (2022) also revealed that many aquaponics were located on rooftops and Tilapia fish is found to be the most common fish species used. Factors identified as motivations for adoption of aquaponics are education, production of food for self-consumption and as a hobby (Suárez-Cáceres et al., 2022).

**Table 11: TRL, SRL, and BRL of aquaponic systems**

<table>
<tr><th>Article</th><th>Country</th><th>System</th><th colspan="2">Product quality and business Feasibility/viability</th></tr>
<tr><td>Zambrano-Prado et al. (2021)</td><td>Egypt</td><td>Aquaponics</td><td colspan="2">• Economically feasible but high operational cost in the short term<br>• TRL, SLR, BRL 3-5</td></tr>
<tr><td rowspan="2">El-Essawy et al. (2019)</td><td rowspan="2">Egypt</td><td rowspan="2">Aquaponics</td><td>Deep water culture</td><td>High quality organic food<br>Profitable in the long run compared to conventional<br>TRL, SLR, BRL 3-5</td></tr>
<tr><td>Aqua-Vegaculture</td><td>High quality organic food<br>Produce more crops with almost 20% less capital expenditure<br>Profitable in the long term compared to conventional<br>TRL, SLR, BRL 3-5</td></tr>
<tr><td>Parada et al. (2021)</td><td>Spain</td><td>Rooftop greenhouse with different substrates</td><td colspan="2">High crop yield when substrates are combined</td></tr>
<tr><td>Martinez-Mate et al. (2018)</td><td>Spain</td><td>Hydroponic + desalinated seawater</td><td colspan="2">High yield</td></tr>
<tr><td>Boneta et al. (2019)</td><td>Spain</td><td>Rooftop Agriculture</td><td colspan="2">Out of 22 different crops produced over 2 years, were tomato, chard, lettuce, pepper and eggplant were the top 5 most productive crops</td></tr>
</table>

### 3.5.3 Rooftop agriculture

According to Boneta et al. (2019) the top most productive crops in rooftop agriculture are tomato, chard, lettuce, pepper and eggplant as case study in Spain. Boneta et al. (2019), using an area of 18 m2 in an open rooftop polyculture garden, determined a significantly high total productivity (10.6 kg m-2 year-1) of 22 different crops. Another study on hydroponics by Voutsinos et al. (2021) compared Lettuce productivity either under artificial lighting or in a Mediterranean greenhouse during wintertime. The study indicated that light and seasonality to be among the significant factors determining lettuce productivity grown hydroponically in a greenhouse where high light intensity and warmer production season appear to produce better quality products. The results are consistent with the findings by (Parada et al. 2021). On the other hand, Chatzigeorgiou et al. (2022) found that lettuce productivity is determined by the use of different combinations of substrates. Comparing four different substrates in a hydroponically produced vine plant their findings indicated that the application of 1.7 perlite produced 1.6-20 times higher yield than Perlite, Perlite-Attapulgite, Perlite-Zeolite, and 8.7 times higher compared with the soil treatment with much lower carbon footprint.

### 3.5.4. Profitability analysis

Analysing the profitability of climate-smart and water-saving technologies requires considering various factors and conducting a thorough financial assessment. The primary goal for farmers and business owners is to maximize their profits. Studies have shown that frontier agricultural technologies, such as hydroponics, aquaponics, and insect farming, are gaining popularity due to their potential for substantial profitability, particularly for medium and small-scale agricultural operations (Benjamin, Buchenrieder, and Sauer 2020; Verner 2017). The following components are the basis for profitability analysis for frontier agricultural technologies in general:

**1. Revenues:** This is sales income generated by selling the produce (e.g., crop sales, fish sales or insect sales).

**2. Total fixed costs:**

- Infrastructure: Costs for setting up greenhouses, hydroponic systems, fish tanks, and related equipment.
- Utilities: Expenses for electricity, water, and climate control systems.
- Labor: Employee wages and benefits.
- Licensing and Permits: Any necessary permits and licenses.
- Interest on Loans: If loan was taken out or the initial investment.

**3. Total variable costs:**

- Variable input costs: Ongoing expenses for purchasing seeds, fertilizer, seeds and nutrients.
- Maintenance: Repairs and regular maintenance costs for equipment.
- Marketing and Distribution: Costs for marketing, advertisement and distributing the produce.

**4. Breakeven point (BEP) calculation:** The break-even point is when total revenue equals total cost. It can be computed as follows:

$$\boldsymbol{BEP} = \frac{Total\ fixed\ costs}{Selling\ price\ per\ unit - Variable\ costs\ per\ unit}$$

Break-even analysis is a vital component when launching a new business. It serves as a crucial tool to determine whether a business is operating at a loss or turning a profit. Additionally, break-even analysis identifies the specific point at which a business begins to generate profit, known as the break-even point (BEP). This point signifies the moment when total revenue equals total cost.

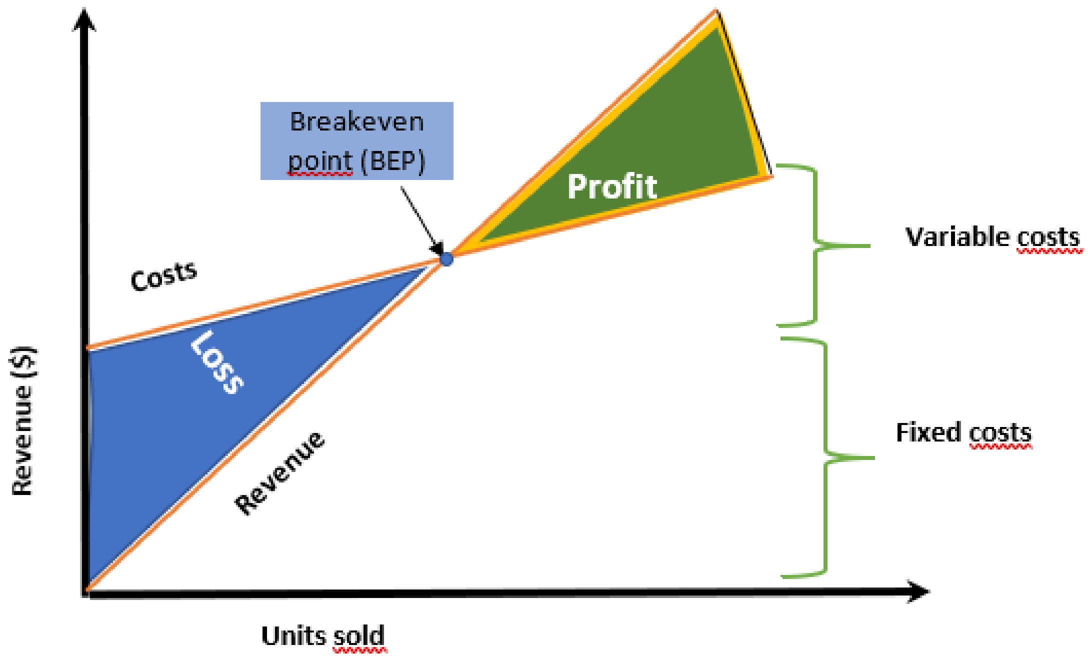


Figure 8: Breakeven point (BEP) analysis

**5. Profit:** After reaching the BEP, any sales beyond that breakeven point will generate profit. The profit is calculated as:

$$\boldsymbol{Profit} = (Selling\ price\ per\ unit - Variable\ costs\ per\ unit)\ \cdot Total\ units\ sold - Total\ fixed\ costs$$

Moreover, it is important to consider potential risks that may impact profitability of frontier agricultural practices, such as disease outbreaks in the fish, extreme weather events, and fluctuations in market prices for the produces. Sensitivity analysis of profits should be considered as important as estimating profits. Relative profitability between competing enterprises under a dynamic environment becomes an important concern beyond the scope of profit per acre and the minimal breakeven yield and output price.

#### *3.5.4.1 Example of BEP analysis of aquaponics*

Among the retained articles, (Asciuto et al. 2019) financial feasibility study of an aquaponic system in southern Italy. The study used sales of baby-leaf lettuces and Nile Tilapia fish to calculate total revenue. The specific establishment for this study was able to produce 2250 lettuce per year. 72 kg of fish (240 tilapias in 2 production cycles. As shown in Table 12 and Table 13, the aquaponic production feasibility analysis reveals given the current prices, the practice yielded a net return of 293.05€. Thus, the breakeven quantity for the two products was lower than those obtained by the pilot unit which was 1829 lettuce heads and 58.5 kg of tilapia (195 fish). The results of this study indicate the breakeven quantity which was lower than those obtained by the pilot is 1829 lettuce heads and 58.5 kg of tilapia (195 fish). The study also suggested certifying aquaponic products as organic products so as to increase the price and thus a higher and significant profit margin.

**Table 12: Revenue and investment cost from aquaponics in the case of southern Italy**

| **Item** | Lettuce | Tilapia | **Item** | Quantity | Cost/unit (€ | Total cost (€) |
|---|---|---|---|---|---|---|
| Unit production per cycle | 50 head/m2 | 36 kg/m 3 | Grow bed | 4 | 61.24 | 244.96 |
| No. annual harvesting cycles | 9 | 2 | Fish rearing tank | 2 | 60.27 | 120.54 |
| Surface area and/or volume | 5 $m^2$ | 1 $m^3$ | Grow beds structure support | 10 | 20.50 | 205.0 |
| Annual production | 2250 heads | 72 kg | Galvanized edge for grow beds | 8 | 1.80 | 14.40 |
| Unit price | 0.60 €/head | 3.00 €/kg | Corrugated pipe for cable protection (180 cm) | 8 | 11.00 | 88.00 |
| Revenue | **1350.00 €** | **216.00 €** | Expanded clay (50 l) | 16 | 4.95 | 79.20 |
| | | | Lava rock (1 kg) | 1 | 1.00 | 1.00 |
| | | | Siphon | 8 | 0.00 | 320.00 |
| | | | Dirty submersible water pump (400 W) | 1 | 39.90 | 39.90 |
| | | | LDPE irrigation pipes (20 m) and fittings | 1 | 60.00 | 60.00 |
| | | | Total cost for facility components | | | 1173.00 |
| | | | Set up | | | 200.00 |
| | | | Total set up cost | | | 1373.00 |
| | | | Cooperative Operating Margin | | | 274.60 |
| | | | Total investment cost | | | **1647.60** |

Source: (Asciuto et al. 2019)

**Table 13: Annual running cost of aquaponics**

| **Annual running cost** | | **Financial feasibility** | | |
|---|---|---|---|---|
| Item | Value | Total Revenue | Total running cost | Net return |
| Depreciation, maintenance, interests | 205.5 | 1566.00 € | 1272.95 € | 293.05€ |
| Labor | 630.0 | | | |
| Energy | 86.00 | | | |
| Water | 36.00 | | | |
| Fish feed | 120.00 | | | |
| Seedling transplants | 175.00 | | | |
| Fingerlings | 20.00 | | | |
| **Total cost** | **1272.95** | | | |

Source: (Asciuto et al. 2019)

#### 3.5.4.2 Example of BEP analysis of hydroponics

In the present SLR, one of the retained articles (Cámara-Zapata et al. 2019) examines the economic feasibility of tomato production using three different systems: an open system with a perlite substrate, a closed system employing the nutrient film technique (NFT), and a hydroponic approach known as the deep flow technique (DFT). These systems were tested under three levels of salinity, which fall within the typical range for irrigation water quality in south-eastern Spain. The salinity levels include Scenario 1 (S0) with an electrical conductivity (EC) of 2.2 dS m−1, Scenario 2 (S1) with 40 mM NaCl and an EC of 6.3 dS m−1, and Scenario 3 (S2) with 80 mM NaCl and an EC of 10.2 dS m−1.

A cost-benefit analysis was conducted to determine whether the revenue generated by each system exceeded its associated costs. As depicted in the Table 14, the cost and revenue structure is based on a two-year average for the soilless production of tomato.

The study reveals that the significance of costs in hydroponic operations varies depending on the cultivation system. An increase in salt concentration in the nutrient solution led to a general reduction in production, which was more pronounced in plants grown using the NFT system. The economic indicators support the conclusion that profitability decreases in the following order: perlite > NFT > DFT. All three soilless growing systems were found to be profitable when using low-salinity water, and perlite demonstrated profitability even with water of intermediate salinity.

**Table 14: Cost benefit analysis of soilless tomato production in Spain**

| Costs and Revenue | DFT | | | Perlite | | | NFT | | |
|---|---|---|---|---|---|---|---|---|---|
| | S0 | S1 | S2 | S0 | S1 | S2 | S0 | S1 | S2 |
| Fixed costs (€ $m^{-2}$) | 4.26 | 4.21 | 4.06 | 3.46 | 3.30 | 3.19 | 3.68 | 3.55 | 3.35 |
| Variable costs (€ $m^{-2}$) | 1.02 | 0.75 | 0.52 | 1.12 | 0.85 | 0.55 | 1.03 | 0.57 | 0.28 |
| Opportunity cost (€ $m^{-2}$) | 0.11 | 0.10 | 0.09 | 0.09 | 0.08 | 0.07 | 0.09 | 0.08 | 0.07 |
| Overhead costs (€ $m^{-2}$) | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 |
| Total costs (€ $m^{-2}$) | 5.61 | 5.28 | 4.89 | 4.89 | 4.45 | 4.03 | 5.02 | 4.42 | 3.92 |
| **Revenue (€ $m^{-2}$)** | **7.1** | **4.94** | **3.24** | **8.16** | **6.05** | **3.78** | **7.48** | **3.93** | **1.81** |
| **Profit** | **1.5** | **−0.2** | **−1.5** | **3.19** | **1.55** | **−0.2** | **2.56** | **−0.4** | **−2.02** |
| Selling price (€ $kg^{-1}$) | 0.74 | 0.70 | 0.66 | 0.78 | 0.77 | 0.75 | 0.77 | 0.74 | 0.71 |
| **Breakeven price (€ $kg^{-1}$)** | **0.58** | **0.75** | **1.00** | **0.47** | **0.57** | **0.80** | **0.52** | **0.83** | **1.55** |

Source: (Cámara-Zapata et al. 2019)

Note: S0, S1, S2 represents different salt levels for the irrigation water (S0; EC = 2.2 dS m−1 ), 40 mM NaCl (S1;EC = 6.3 dS m−1 ), and 80 mM NaCl (S2; EC = 10.2 dS m−1 ).

Overall, the key performance indicators of frontier technologies identified are higher yield, short period of growing season compared to conventional, no need to use chemicals, save irrigation water and adaption to extreme conditions that allows farmers to produce in harsh environments.

# 4 Conclusions

The present SLR showed that research in Mediterranean countries is already focusing on the application of smart agriculture systems to increase productivity while guaranteeing healthy and nutritious food as well as keeping the environmental impact low. In particular, European Mediterranean countries such as Spain and Italy are leading the research. For instance, Spanish research leads the topic of rooftop agriculture. In case of African Mediterranean countries, Egypt is the one involved most in research on frontier agriculture systems. The SLR shows a capability of frontier agriculture to increase circularity and sustainability also in Mediterranean area. Indeed, the evaluated cultivation systems demonstrated the capacity to reuse and optimize cultivation resources, while creating income, fostering social inclusion of minorities (e.g., women, refugees), and creating different ecosystem benefits (notably: ). In terms of FNS, some articles specifically highlighted a capacity of small-scale hydroponic, aquaponic or rooftop agriculture, to ensure daily self-household production, with important consequences on food security of less advantaged families. In particular, most of the papers showed a TRL, BRL and SRL in the range of 3-5 points.

Based on the SLR results, the proposed KPIs at the micro-level that could be useful for demonstration cases to estimate the effect on the WEFE Nexus are:

- 50% of women or 40% of disadvantaged people (e.g., refugees, elderly, disabled people) involved on totality of people involved in the demonstration case;
- 50% of irrigation water coming from sustainable/alternative resources or recirculated within the system in the demonstration case (e.g., rainwater, saline water, recycled water from aquaponic system, closed loop hydroponic system);
- 50% of fertilizer or cultivation substrate coming from organic and recycled resources (e.g., compost, coconut fiber, fish organic wastes), or
- 30% of energy coming from renewable energy sources (e.g., solar panels), whereby renewable energy ought not to be used to deplete, e.g., water resources through extensive water pumping from ground water resources.

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# Annexes

## Annex I: Meaning of the different TRL levels

| MATURITY LEVEL | DESCRIPTION |
| --- | --- |
| TRL1 | Basic principles observed |
| TRL2 | Technology concept formulated |
| TRL3 | Experimental proof of concept |
| TRL4 | Technology validated in lab |
| TRL5 | Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| TRL6 | Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| TRL7 | System prototype demonstration in operational environment |
| TRL8 | System complete and qualified |
| TRL9 | Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space) |

Source: Bruno et al. (2020, p. 370)

## Annex II: Meaning of the different BRL levels


Source: https://www.linkedin.com/pulse/business-readiness-levels-complete-guide-academics-/

## Annex III: Meaning of the different SRL levels

| MATURITY LEVEL | DESCRIPTION |
|---|---|
| SRL1 | Identification of the generic societal need and associated readiness aspects |
| SRL2 | Formulation of proposed solution concept and potential impacts; appraisal of societal readiness issues; identification of relevant stakeholders for the development of the solution |
| SRL3 | Initial sharing of the proposed solution with relevant stakeholders (e.g. through visual mock-ups): a limited group of the society knows the solution or similar initiatives |
| SRL4 | Solution validated through pilot testing in controlled environments to substantiate proposed impacts and societal readiness: a limited group of the society tests the solution or similar initiatives |
| SRL5 | Solution validated through pilot testing in real or realistic environments and by relevant stakeholders: the society knows the solution or similar initiatives but is not aware of their benefits |
| SRL6 | Solution demonstrated in real world environments and in co-operation with relevant stakeholders to gain feedback on potential impacts: the society knows the solution or similar initiatives and awareness of their benefits increases |
| SRL7 | Refinement of the solution and, if needed, retesting in real world environments with relevant stakeholders: the society is completely aware of the solution's benefits, a part of the society starts to adopt similar solutions |
| SRL8 | Targeted solution, as well as a plan for societal adaptation, complete and qualified; society is ready to adopt the solution and have used similar solutions on the market |
| SRL9 | Actual solution proven in relevant societal environments after launch on the market; the society is using the solution available on the market |

Source: Bruno et al. (2020, p. 373)

## Annex IV: Articles retained for ecosystem services, carbon footprint, economic performance and TRL, BRL and SRL

| Topic | Description | Authors |
|---|---|---|
| **Environmental Benefits** | Ecosystem | (Alotibi et al. 2023), (Boneta et al. 2019a), (Duarte and Caçador 2021), (FAO 2015), (Kir et al. 2022), (Muñoz-Liesa et al. 2022), (Platis et al. 2021), (Romero-Gámez and Suárez-Rey 2020), (Rufí-Salís et al. 2021), (Toboso-Chavero et al. 2021), (Verner 2017), (Voutsinos et al. 2021) |
| | Carbon footprint | (Barla, Salachas, and Abeliotis 2020), (Ben Hamed et al. 2021), (Chatzigeorgiou et al. 2022a), (Maaoui, Rachid, and Hajjaji 2023), (Martin-Gorriz et al. 2021), (Martinez-Mate et al. 2018), (Parada, Gabarrell, et al. 2021), (Rafik et al. 2021), (M. Rufí-Salís et al. 2020), (Martí Rufí-Salís et al. 2020) |
| **Socio-economic** | Productivity, income, food security | (Alotibi et al. 2023), (Boneta et al. 2019a), (Ceccanti et al. 2022), (Chatzigeorgiou et al. 2022a), (Giordani et al. 2023), (Greenfeld et al. 2022), (Kir et al. 2022), (Parada, Gabarrell, et al. 2021), (Sadek, Kamal, and Shehata 2023), (Sinesio et al. 2021), (Suárez-Cáceres et al. 2022), (Toboso-Chavero et al. 2021), (Verner 2017), (Vlahos et al. 2019), (Zambrano-Prado et al. 2021) |
| **TRL, SRL, BRL** | Profitability, viability, | (Asciuto et al. 2019), (Boneta et al. 2019a), (Cámara-Zapata et al. 2019), (El-Essawy, Nasr, and Sewilam 2019), (Michalis et al. 2023), (Suárez-Cáceres et al. 2022), (Verner 2017), (Voutsinos et al. 2021) |

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