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From microgarden technologies to vertical farms: Innovative growing solutions for multifunctional urban agriculture.

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Abstract

In response to the growth of urban population and the reduction of resources availability (e.g., arable land, water, and nutrients), new forms of agriculture that can be developed also in urban environment are gaining increasing popularity. Urban agriculture constitutes a viable opportunity for improving the city food security, also fostering local and circular economies, social inclusion, and environmental sustainability. In the different World regions, a diversity of urban farming systems is encountered, with technological levels varying in response to the local socio-economic context, infrastructural networks, and environmental conditions. In developing economies from the South of the World, most interesting innovations include simplified hydroponics, organoponics, and microgarden technologies; whereas, in the Global North, innovative solutions for plant cultivation also include rooftop greenhouses and indoor vertical farms with artificial lighting where vegetable crops, mushrooms, and algae may be grown. Beside plant growing solutions, innovation may also stand in the system integration and mutual relationship with the urban fabric (e.g. in terms of resource use or ecosystem service provisioning), or in the business model adopted. The present review paper will describe a number of innovative solutions for plant cultivation in the urban environment, with a special consideration of the economic, environmental, and social sustainability.

Keywords: urban horticulture, building integrated agriculture, vertical farming, microgarden technologies, business models

INTRODUCTION

With the deadline of Millenium Development Golas (MDGs) in 2015, 193 nations worldwide agreed setting new global objectives of development to reach by the next 15 years (Joshi et al., 2015). The new identified goals, also named Sustainable Development Goals (SDGs), are divided in 17 target categories overall related to environmental, social and economic issues (Stevens and Kanie, 2016). In this framework, the development of a green economy aiming to reduce environmental impact through the increase of renewable energies, consumption reduction and wastes recycle (Loiseau et al., 2016), is emerging as a new mindset to overcome the current "Anthropocene epoch" and the consequent lacking of resources (Steffen et al., 2007). Furthermore, while world population in cities is growing, the realization of a sustainable development is increasingly becoming a matter of urban fabric, making crucial the identification and implementation of innovation in food systems that may provide city nutrition and food security (Mougeot, 2006). Indeed, for a long time the food system has been considered a rural issue, most of the time overlooked by architects and urban planners involved in the design and planning of cities (Pothukuchi and Kaufman, 2000). To date, the concept of "edible cities", also defined as Continuously Productive Urban Landscapes

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(CPUL) (Bohn and Viljoen, 2011), is becoming more familiar to urbanists and evolving through the key role of urban agriculture.

Urban Agriculture (UA) is a multifunctional practice that integrating the urban fabric may support achieving mutual benefits through the offer of numerous ecosystem services (Russo et al., 2017). The main benefits and services are related to food security, urban micro-climate management, carbon footprint reduction, social inclusion, income generation, education and health (Van Veenhuizen, 2014). Depending on business model and geographical location, UA may take different forms that may be classified into three main categories (Specht et al., 2016a). The first category is represented by subsistence family gardens and micro-enterprises in emerging cities of Global South, where UA is mostly applied to ensure food nutrition and small incomes (Orsini et al., 2013). A second group involves experiences of community based urban agriculture in the cities of Global North, in which vacant spaces have been used through the years for low-tech food provisioning during periods of economic crisis (Opitz et al., 2016). Finally, the last group refers to environmentally controlled and technologically advanced business-oriented food enterprises, especially occurring in the megacities of Asia and rich countries of developed world under the comprehensive name of Plant Factories (Kozai et al., 2016).

Despite UA could be performed on empty lands within and in the fringe of the city, competition for urban soil as well as risks connected to heavy metals contamination are often leading to the application of soilless productive systems (Pennisi et al., 2016). With soilless farming is intended any method of cultivation without soil, applying hydroponic, aeroponic or aquaponic techniques (Tajudeen and Taiwo, 2018). These systems, which may also be integrated on building structure (Specht et al., 2014; Thomaier et al., 2015), can present different technological complexity depending on their framework of application. Accordingly, while advanced soilless systems can be used for production optimization in the sophisticated vertical farms of developed nations (Despommier, 2010), Simplified Hydroponic (SH) or Simplified Soilless Cultivation (SSC) systems represent the most suitable solution for global hunger reduction in low-income countries (Bradley and Marulanda, 2001). This article aims to offer a general overview on the main soilless technologies for urban agriculture in different socio-economic contexts of World regions.

LOW-TECH SOLUTIONS

1. Simplified Soilless Cultivation systems (SSC).

The application of low-tech micro-gardens based on soilless systems represents the most suitable solution for urban horticulture when targeting the poorer strata of population. Indeed, thanks to the inexpensive and easy availability of constructing materials as well as to the simple management (Fecondini et al., 2009; Orsini et al., 2013), SSC can be used in disadvantaged urban and peri-urban contexts of both Global North and South of the world, accomplishing specific multifunctional benefits of urban agriculture. Indeed, an easy and domestic self-supply of fresh fruit and vegetables is a substantial aspect for the achievement of food security and nutrition in low-income urban realities (Maxwell et al., 1998; Zezza and Trasciotti, 2010). Furthermore, SSC can facilitate employment, social integration and emancipation of lower classes and minorities (Smit and Bailkey, 2006; Fecondini et al., 2010; Orsini et al., 2010a), as demonstrated by women communities in the suburbs of Latin America (Mezzetti et al., 2010; Orsini et al., 2010b). In this framework, low-tech urban agriculture can become a source to integrate household income (Orsini et al., 2009; Poulsen et al., 2015) and an adaptive response to economic crises, preserving from food prices fluctuations and inaccessibility (Kutiwa et al., 2010).

Simplified systems present specific novelties for developing countries in which resources efficiency and products safety may signify distinctive issues. Particularly, benefits are related to the possibility to cultivate on poor, saline and contaminated soils, optimizing the use of fertilizers, herbicides, water and labor, and improving plant density, uniformity and productive cycles with overall increase of yield (Samangooei et al., 2016; Tajudeen and Taiwo, 2018). A greater independence from growing season and climatic conditions is another interesting aspect when combining soilless with protective structures, such as shading screens applied in dry season to protect from sun excessive radiation (Gianquinto et al., 2007). In the case of tropical countries, SSC may also represent a solution to overcome floods occurring during heavy rain periods and making on soil cultivation almost impracticable (Orsini et al., 2013). Beside ground level applications, these systems are also a valuable answer to low-tech rooftop agriculture, guaranteeing higher yield in smaller space and not affecting roof structural loads thanks to the limited weight of components (Orsini et al., 2014; Rodríguez-Delfín et al., 2017).

With specific regard to water optimization in SSC, wastewater can be used as an inexpensive and year-round available irrigating and fertilizing source, especially in arid and semi-arid countries where water recycle represent a vital aspect (Buechler et al., 2006). However, wastewater reuse should take into account connected risks. According to the assessment for water quality in urban agriculture made in Nairobi, Kenya by Karanja et al. (2009), major hazards include contamination from pathogens and pesticides, together with heavy metals uptake (Mapanda et al., 2007) and occurrence of disease vectors (Klinkenberg and Amerasinghe, 2006).

Symplified floating hydroponics.

Simplified hydroponic presents considerable popularity in developing countries especially of Latin America and Caribbean area, where the FAO (Food and Agriculture Organization of the United Nations) promoted pilots and training for the achievement of global food security and socio-economic goals (Bradley and Marulanda, 2001; Izquierdo, 2007). It can be applied in its "pure" form as simplified floating systems, showing great potentialities in terms of leafy vegetables production and restrained starting and running costs. The technique consists on the use of floating materials, such as polystyrene, to support plants contained in net pots and placed on a nutrient solution in direct contact with roots (Tajudeen and Taiwo, 2018). Most of containers for nutrient solution are represented by squared boxes in recycled wood, coated with a waterproofing polymer and with a limited dimension (generally around 1 m^2) to facilitate system management (Figure 1) (Orsini et al., 2010a; Tajudeen and Taiwo, 2018).

Despite the limited costs and request of labor, simplified floating systems may present some constrains. In certain environmental conditions, high temperatures could determine a lower level of oxygen in the nutrient solution therefore affecting roots oxygenation (Orsini et al., 2013). Issues may also occur in countries facing diseases (e.g. malaria, dengue), where stagnant water could become a reproductive basin for the vector (Klinkenberg et al., 2008). Furthermore, water quality and fertilizers accessibility could also become a critical problem, making system management difficult in case of saline or contaminated irrigation sources. In this context, use of harvested rainwater represent the most suitable solution, thanks to a low electrical conductibility and the limited microorganisms content (Orsini et al., 2013).

Figure 1. The simplified floating system. (1) Rendering of the system and (2) exploded system design. (3) Images of simplified substrate growing systems in the cities of (4) Trujillo (Peru) and (5) Lima (Peru).

Simplified substrate systems.

Beside the use of “pure hydroponic”, SSC can include simplified substrate systems consisting on variable containers filled with a growing medium watered with a nutrient solution. They can be adopted in different climatic conditions and use diverse substrates depending on local availability, as in the case of rice hulls mixed with gravel to cultivate in peri-urban microgardens in Trujillo, Peru (Orsini et al., 2010b). Potentially, every typology of container could be adapted to the system. Available materials could vary depending on investment budget, ranging from recycled plastic bags or buckets in extreme poor cases, to constructed wooden boxes waterproofed with plastic films in situations of major accessibility (Orsini et al., 2010b; Orsini et al., 2013).

In the case of wood containers, the *Caixa System* is a peculiar form of microgarden technology developed in the peri-urban area of North-East Brazil applying coconut fiber grinded from nuts (*Cocos nucifera* L.) as a growing substrate (Gianquinto et al., 2007). This system presents very contained building costs ($US 7-30) and a slight slope to recollect and reuse the drained nutritive solution (Orsini et al., 2009). The *Caixa* results particularly suitable for larger species requiring more anchorage for the roots and therefore hardly adaptable to other soilless structures (e.g., floating system), hosting from 5 to 8 plants on a surface of 1 m^2 (Figure 2) (Orsini et al., 2009).

Within simplified substrate systems is also comprised the so called organoponic, which specifically applies organic substrate such as compost or organic matter of diverse origin to grow plants (Orsini et al., 2013). This kind substrate is an optimal solution in case of low-fertile soils in low-income areas, avoiding costs for chemicals through the reuse of organic wastes such pruning, house leftovers and animal manure. Organoponics found great application in Venezuela and Cuba (Cruz and Medina, 2003; Tixier and De Bon, 2006), where their spreading was mainly promoted by governmental policies. In Cuba, organoponic was originally supported by governmental programs starting from the ‘80s, when implications of

Cold War determined severe issues concerning food security (Altieri et al., 1999). Ever since, the successful application of organoponics continued until now, counting more than 200 cases and providing half of fruit and vegetable needs to Havana residents (Orsini et al., 2013).

Figure 2. The Simplified substrate growing system. (1) Rendering of the system and (2) exploded system design. Images of simplified substrate growing systems in the cities of (3) Teresina (Piaui, Brazil), (4) Trujillo (Peru), (5) Abidjan (Ivory Coast), (6) Boipeba (Bahia, Brazil), (7) Lima (Peru) and (8) Tidjikja (Mauritanie).

The garaffas pet system.

The *Garaffas PET System*, is a rudimental from of NFT developed in Brazil and composed by inclined lines of recycled plastic bottles (garaffas) hold up by a wooden structure (Figure 3). In particular, the system takes advantage of a gravity flow coming from a 300 liters volume tank placed at 2.5 meters of height. Hydraulic pipes transport the nutrient solution in the lines of *garaffas* with a slope of 22-24%, filled with burned rice hulls (Gianquinto et al., 2007; Orsini et al. 2009). Excess solution is recollected in a drainage tank and moved back to the upper one for recirculation. Requested labor is around 20 minutes twice per day when operated manually, or less than 5 minutes when using a pump (Gianquinto et al., 2007). Considering a 18 m^2 *garaffas* microgarden with 20 lines of plastic bottles, building costs run around $US 180 (Gianquinto et al., 2007).

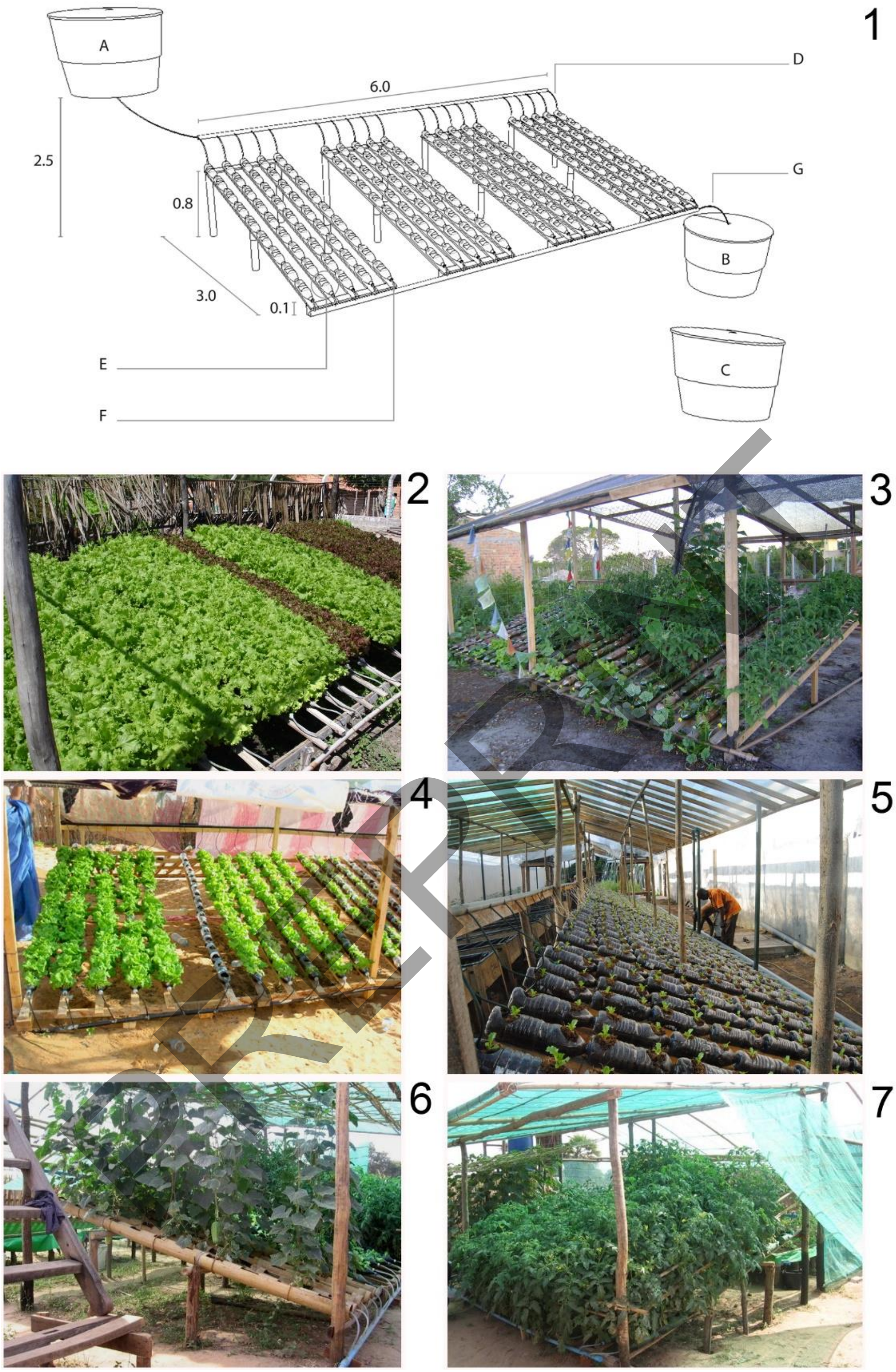

Figure 3. The Garaffas PET growing system. (1) Schematic drawing of a module, including a top (A) and a drainage (B) tanks, as well as a fresh nutrient solution reservoid (C). The system is fitted with a gravity flow drip-irrigation system (D) that deliver the nutrient solution to 20 lines of recycled plastic bottles (E). Excess nutrient solution is then drained to a recollection pipe (F) which is connected (G) to the drainage tank (B). Images of Garaffas PET modules in the cities of (2) Teresina (Piaui, Brazil), (3) Boipeba (Bahia, Brazil), (4) Tidjikja (Mauritanie), (5) Abidjan (Ivory Coast), (6) and (7) Magway (Myanmar).

HIGH-TECH SOLUTIONS

1. Building integrated rooftop greenhouses (i-RTGs)

Rooftop Agriculture (RA) (Orsini et al., 2017) is a form of building-based farming which can apply different typologies of technology to foster the so-called zero-acreage production of fruit and vegetables (Z-farming, Specht et al., 2016a; Thomaier et al., 2015). Although rooftop production in open-air conditions could achieve good performances in certain periods of the year adopting the right technology (Sanyé-Mengual et al., 2015), best results and productive extension can be obtained in protected environments. In this framework, Rooftop Greenhouses (RTGs) can be applied on top of buildings and usually features soilless systems (e.g., hydroponic, substrate, aeroponics) to produce a wide variety of horticultural products (Cerón-Palma et al., 2012; Pons et al., 2015). Closed-loop irrigation systems are mostly indicated in RTGs, guaranteeing the best environmental performances and rewarding the farmers with the savings of fertigation inputs (Ehret et al., 2001; Montero et al., 2017a). Savings can also be achieved by the use of rainwater, to be integrated with tap water when not enough to satisfy cultivation requirement (Sanjuan-Delmás et al., 2015).

RTGs usually present a high technological degree, therefore concentrating cases especially in the developed side of the world. Most of running cases are represented by private or public organism focused on commercial and innovation goals, although feasibility for social-educational aims has also been proved, for instance involving schools (Nadal at al., 2018). North America especially shows a number of commercial farms applying hydroponic systems and controlled environmental technologies for vegetables production, as in the case of Lufa Farm in Montreal, Canada, or Gotham Greens in New York, US (Buehler and Junge, 2016). Europe is also developing interest for RTGs, where some commercial and research cases also exist (Sanyé-Mengual et al., 2018). Despite the advanced technological level, most of cases present a net separation between the greenhouse and the hosting building below. However, their integration can determine metabolism improvement of both parties with overall consequences on cities sustainability, as demonstrated by the pioneering Integrated Rooftop Greenhouse (i-RTG) at the research center of ICTA, near Barcelona, Spain (Sanjuan-Delmás et al., 2018).

With i-RTG is intended a rooftop greenhouse integrating flows with building metabolism to achieve an improvement of resources efficiency (Sanyé-Mengual et al., 2014). This symbiosis, which can be applied on both new and existing buildings, specifically addresses the reuse of residual resource flows (energy, water and CO_2) that recirculating between the building and the greenhouse can help decreasing the environmental impact related to global emissions and contemporarily optimize production inputs (Nadal et al., 2017). For instance, it was evaluated that metabolisms integration can reduce building energy cooling by recirculating the air produced by the greenhouse passive cooling system within the structure (Caplow and Nelkin, 2007). On the contrary, the greenhouse can work as a thermal solar collector, heating the above building through surplus energy cumulated during the day (Montero et al., 2017a). Other passive climate control systems can be favored by specific infrastructure, such as a double skin façade on building surface flowing the air heated by sun radiation into the productive area (Nadal et al., 2017). However, building superstructures, as well as materials and protection components imposed by fire and wind safety codes, often reduce light transmissivity compared to traditional greenhouses with overall consequences on yield (Montero et al., 2017a). In these cases, production in i-RTGs may be improved by enhancing greenhouse transparency or CO_2 concentration or evaluating the possibility to anticipate growing season to be more competitive against non-heated standard greenhouses (Montero et al., 2017b).

Figure 4. Examples of rooftop farms. *Open-air rooftop gardens:* (1) AgroParisTech (Paris, France); (2) Post office La Chapelle (Paris, France); (3) Kitchen rooftop garden in Barcelona at residence of Joan Rieradevall Pons (Barcelona, Spain); (4) Therapeutical rooftop garden managed by IRTA (Barcelona, Spain); (5) and (6) Rooftop garden in social housing buildings of Via Gandusio (Bologna, Italy); (7) Rooftop aquaponic greenhouse at UrbanFarmers (The Hague, The Netherland); (8) and (9) The experimental integrated-Rooftop Greenhouse (i-RTG) at IRTA (Barcelona, Spain).

2. Plant factories with artificial lighting (PFALs)

The most high-tech form of urban agriculture is embodied by the Plants Factories with Artificial Lighting (PFALs) (Kozai et al., 2016), also referred to as Vertical Farms by some authors (Despommier, 2010; Birkby, 2016). The PFALs are farming systems based on the control of all environmental factors that can affect plant growth, including temperature, relative humidity, light and CO_2. Therefore, the production results protected from outdoor conditions, adopting closed and thermally insulated cultivation chambers communicating with the external environment only for limited air exchange (Kozai and Niu, 2016). This net separation is a primary quality of this form of urban agriculture, making the system completely resilient to outside extreme climatic conditions and diseases (Kozai, 2019), contemporary allowing a continuous yearly production free from pesticides. Another interesting implication of PFALs is connected to soil consumption. Indeed, thanks to the possibility to cultivate on more levels, high quantities of product can be produced in less space, therefore reducing the current global concern for agricultural land consumption (Beacham et al., 2019). Last, the great closeness to consumption centers achievable determines reduced transport and storage, with overall benefit on carbon footprint (Specht et al., 2016b).

The PFALs apply an indoor technology to perform cultivation, usually explicated through the use of LED lights, hydroponic systems and sensors to control environmental factors. Compared to other light typologies, LED technology present interesting qualities for the development of plant factories, particularly showing higher luminous efficiency, optimal spectral selection (Pennisi et al., 2019a, b), low surface temperature, long lifetime and good cost performances (Kozai, 2016). Besides, hydroponic provides optimal solution to be adopted in PFALs, especially in the forms of NFT, ebb and flow or aeroponic systems. An alternative solution may be represented by growing columns filled with substrate (e.g., perlite), where plants are vertically grown (Beacham et al., 2019) although at the expenses of possible heterogeneity in the distribution of nutrients (Linsley-Noakes et al., 2006). Hydroponic is particularly useful for automation of management. In the case of application of a closed system it can help water savings (Pennisi et al., 2019c), achieving a water use efficiency 30-50 times higher than open-air or greenhouse production (Kozai, 2013). Use of sensors also contribute to an easier management, especially of the root-zone where pH, electrical conductivity, oxygen and temperature can be kept under control (Son et al., 2016). These outputs can also be connected to other environmental measurements through Internet of Things (IoT) solutions, therefore allowing producers to maintain a standardize production and optimize costs (Wu et al., 2016).

Despite the aforementioned potentialities of PFALs, some limitations are still represented by the high constructing and running costs, making this investment more economically advantageous than traditional greenhouses only in certain contexts (Avgoustaki and Xydis, 2020). This aspect determined a worldwide distribution particularly concentrated in rich countries of Asia, North America and Europe, where cultivation is often performed in large industrial spaces, warehouses or also transportation containers (Thomaier et al., 2015). Cases are usually commercial businesses growing different products including leafy vegetables (e.g., lettuce, basil, microgreens), medicinal plants (e.g., cannabis), small fruit (e.g., berries), edible flowers and seedlings (e.g., grafted vegetable) (Kozai, 2013), also including peculiar experiences of mushrooms and algae production. By 2022, the vertical farming market is expected to reach a global value of 5.80 billion USD (Markets and Markets, 2019).

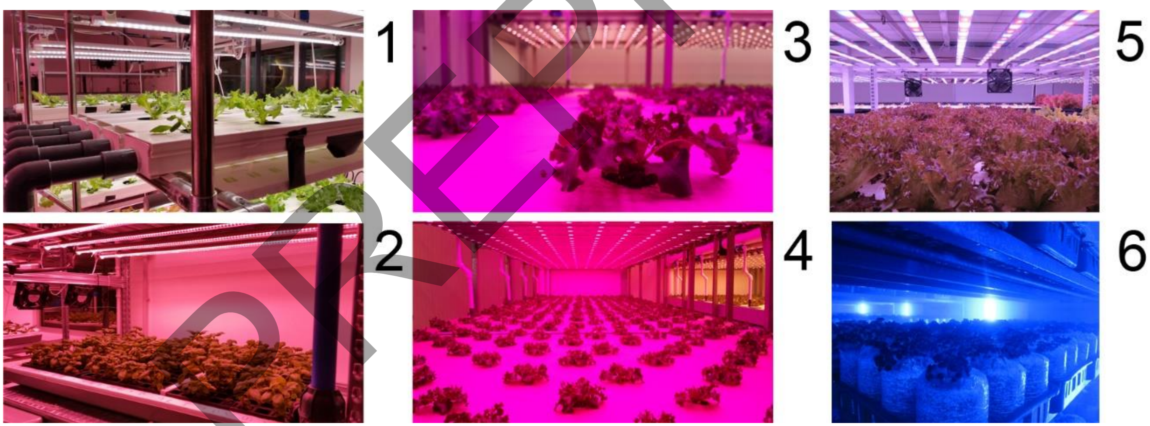

Figure 5. Examples of indoor vertical farms with artificial lighting: (1) and (2) Agricola Moderna (Milano, Italy); (3) and (4) Brightbox (Venlo, The Netherlands); (5) Shenter (Taichung, Taiwan); (6) Magical Mushroom Tribe (Taichung, Taiwan).

CONCLUSIONS

Soilless agriculture represents an optimal solution to face resources limitation and environmental world challenge, thanks to an optimization of cultivation inputs and low space consumption. For what concerns the Global South of the World, proper transmission of knowledge, as well as technical assistance, are fundamental aspect to reach the real potentialities for a zero-hunger application (Orsini et al., 2013). On the other hand, developed countries still have to completely discover and accept innovation technologies available for urban farming system, which in some cases are still perceived by citizens as an "unnatural" way to cultivate (Specht et al., 2016b).

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