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Vertical farms for vegetables

Until recently, vertical farms were an exception in the market, but now this high-tech agricultural sector is rapidly gaining ground in urban centers of Asia, North America and Western Europe. However, their economic viability and agronomic interest, compared to field crops or greenhouses, are far from established. Why, then, do some investors choose to follow this path of innovation? What, exactly, are the technical solutions required to produce in confined buildings, without natural sunlight? And, does this business model have future prospects?

Urban agriculture is now promoted as a vector of sustainable food, quality of life and community engagement. Most often, though, it consists of small-scale home and leisure activities: shared neighborhood gardens, potted crops on balconies or green rooftops, etc. These "initiatives" are confined to a niche by the lack of land and the intermittence of citizen involvement. The artificial environment of the city, with its soil and air pollution, building shadows, and impermeable pavement, hinders any large-scale deployment of urban gardens. Thus, their contribution to the populations' food supply seems doomed to remain marginal.

On the opposite side of the social and market spectrum is urban agriculture for industrial and production purposes, and more specifically on vertical farms. With advancements in LED lamps, robotics and information technology, multi-level indoor production units with reduced footprints are being created, dedicated to the intensive cultivation of plants and vegetables, mostly salads. Contrary to greenhouses, these high-tech farms do away with natural light and cut all dependance to their outside environment. This version of urban agriculture has strong ambitions: mass production of quality food products, at any time, under any climate, close to consumers, and without the use of pesticides, all at market prices.

Even now, these indoor farms remain the exception, with very few having crossed the three compulsory phases of industrial development: the R&D phase, "characterized by the removal of major uncertainties (technical characteristics of the product, approval)"[1]; the pre-industrialization phase, where the doubts about industrial costs are lifted; and the steady state phase, where the production reaches wide circulation in the broader market. They are still on the edge of the economy dominated by techno-scientific promises, startups, and venture capital, which raises specific assessment difficulty[2].

The first part of this note reviews historical elements and describes the main issues addressed by the new production systems. The next section provides an overview of the equipment currently in operation around the world. Finally, the third, more future-oriented, part of the paper evokes the reality tests these vertical farms will have to overcome if they are to deploy on a large scale.

1 - From the myth of horticultural R&D to modern-day achievements

In the past, many researchers and engineers have tried to develop small-scale, confined farming units. The "vertical farm" was therefore developed during the twentieth century as an R&D challenge, a *rational myth* capable of mobilizing and "designating the technological barriers to be lifted, on which to orient the scientific effort and public subsidies"[3]. These programs, which aimed at controlling environmental conditions, were also motivated by messianic aspirations to control nature, and sometimes, by millenarist fears.

From 1949 on, as the cold war drove scientific exploration, the "phytotrons" made it possible to study the relationship between genotype and phenotype. Even at the time, computer systems played a central role, giving scientists "control of control"[4]. For its part, the US military-industrial complex developed "life support systems" for travel in space or in polar territories. In addition to NASA's projects during the Cold War[5], General Electric ran a "perfect tomato" program in the 1970s, which was ultimately unsuccessful[6].

The pioneers of verticalization had specific technical goals, achievable thanks to advances in science and technology. But they also sought to answer some of the major issues of their

1. Ponssard J.-P., 1993, "Gérer la recherche-développement comme un défi. Quel rôle pour la planification?", *Cahiers d'économie & sociologie rurale*, 28.
2. Joly P.-B., 2015, "Le régime des promesses technoscientifiques", in Audétat M. (ed.), *Pourquoi tant de promesses ?*, Hermann.
3. Quote from Béfort N., 2016, *Pour une mésoéconomie de l'émergence de la bioéconomie*, Université de Reims, p.59, to sum up concepts first elaborated by A. Hatchuel in an effort to analyze R&D as collective action, including material and imaginary/ideological dimensions.
4. Munns D., 2015, "The phytotronist and the phenotype", *Studies in History and Philosophy of Biological and Biomedical Sciences*, 50, 29-40.
5. Wheeler R.M., 2017, "Agriculture for space: People and places paving the way", *Open Agriculture*, 2-1, 14-32.
6. Boards G.E., 1981, "The engineered tomato", *Electronics & Power*, march, 206.

time. Thus, the desire to fight against hunger in the world was a motivator in the late 1920s, as seen with the excitement around the work of W. F. Gericke on hydroponics. At the 1964 horticultural show in Vienna, O. Ruthner presented a 41-meter tower that is often seen as a landmark in vertical farming. This engineer tried to circumvent the difficulty of stacking crops through a system of rotation towards the sun, supplemented by artificial lights. The FAO then assessed its usefulness in fragile regions[7], but the scientific community lost interest after changes in population forecasts at the beginning of the 1970s and during the period of Détente.

More surprisingly, a lineage of futurologists, ecologists and architects challenged by environmental degradations, have considered intensifying agriculture without soil in an urban context as a way to "give land back" to Nature. The association between vertical farms and the *land sparing* approach was explicit in the writings of D. Despommiers, who popularized the concept of vertical farm at the beginning of the 2010s[8]. But before him, it can be tracked down as far back as science-fiction of the 1950s[9], and the idea was featured in scientific articles by M. Takatsuji, a Japanese researcher who designed the first plant factories for Hitachi in the 1970s[10].

The current confined production units, known as vertical farms, will share the history of so-called "controlled environment agriculture"[11] with their predecessor, greenhouses. In both cases, "light recipes" affect the quantity, duration and intensity of light radiation. Sensors and information systems regulate each growth parameter to approach the "agronomic potential" of the plant. In glass greenhouses, the red/ blue ratio, which controls the development and structure of the plant, is optimized with additional filters and lighting, according to specific objectives (compactness, branching, color of the foliage, rate of essential oils, etc.)[12]. However, greenhouses remain dependent on climate variability (temperature, hygrometry), and the uncontrollable component of sunshine may erase some benefits of complementary lighting. Therefore, a strong argument in favor of vertical farms is that it may be simpler to do without natural lighting altogether. This dream has been revived in recent years as light-emitting diodes (LEDs) appeared on the market (during the 2000s), which produce little heat, and whose price is rapidly decreasing.

The question of yields, and more generally that of the control of the vegetative cycle, arises as soon as we consider these methods of productions. The press releases of the firms involved in these efforts are very optimistic, with some claiming production 120 times greater than open-field cultivation (Agricool, strawberry production, France), or 350 times higher (Aerofarms, leafy vegetables, USA). A few scientific articles seem to point in the same direction[13]. The interpretation of these figures, however, must take into account the number of cycles and stages of the installation: 10 lettuce cycles on 10 floors (high configuration), instead of one in the open ground (low hypothesis), provide a production cycle multiplied by 100 over a year, to which is added a yield bonus to hydroponics, related to the better absorption of nutrients.

In general, studies on the subject show levels of production close to those obtained with the usual technical itineraries, rather than a quantum leap of productivity. There is no complete life-cycle analysis available so far, but researchers have combined lettuce growth models with greenhouse and building climate models to evaluate results at different latitudes[14]. The same type of analysis was conducted using data recorded at two experimental sites in Chiba[15]. While the control of releases to the environment seems real, the recycling of nutrients in the context of loops (as in aquaponics) remains marginal. The system reduces the use of non-replaceable resources (phosphorus, water, land), but may lead to a high electricity consumption, and the use of LEDs raises the issue of rare earth depletion.

Finally, the advocates of vertical farms emphasize the ecofriendly aspect of their efforts. Thus, the producer Plenty, insists on the new technologies used to develop growth models (LEDs, infrared cameras, etc.) and on the use of biocontrol (ladybugs). Another producer, Agricool, mentions the pollination of its strawberry plants by bees/drones, and their use of renewable energy. Schemes inspired by industrial ecology are supposed to limit the use of non-renewable resources. Water consumption is optimized. GMOs are rarely promoted, while the claim to sell healthy products, even equivalent to certified organic produce, is made frequently in the United States (where the organic label does not exclude out of the ground production).

2 - A techno-industrial agriculture

In 2017 there were nearly 400 indoor farms in operation worldwide and at least as many "projects" in development, prototyping phase or related to research and education[16]. The specialized press frequently reports new ones. The main hotspot is in Asia, which has more than 90% of the identified facilities: Japan is a pioneer with nearly 200 plant factories in operation; Taiwan[17] follows closely, with a hundred farms installed; then China, with 10 factories in service but 160 projects announced.

All of these identified vertical units combine at least four components:

- Soilless production, allowing installation in all places. Water loaded with nutrients is provided by pumps and gutters (hydroponics) or sprayed on the roots in fog (aeroponics).
- Climate control, incorporated directly into the design of the buildings. This aims to use exchanges with the outside to control the internal climate, including the temperature, humidity, ventilation, enrichment of the air in CO_2, and control of the pathogenic pressure.
- A sophisticated lighting system, to meet plants' requirements for photosynthesis, since stacking crops hinders light to nourish them.
- Small plant species, especially salads and herbs, since the inter-level height differences between crops must be reduced as much as possible.

To qualify these production systems, one could speak of "multi-stage cultivation in a confined environment"[18]. But more commonly used designations – such as *plant factories* in Japan, *indoor agriculture* or *vertical farm* in the United States, *city farming* in the Netherlands – tend to blur the border with conventional greenhouses which rely on sunlight and may or may not employ artificial lighting. Available data are not always reliable: industrial secrecy and a number of variables such as footprint, number of floors, production area estimates, vegetables produced, target markets, etc., make direct comparisons difficult, and lists of production units vary according to the criteria and definitions used.

7. Januszkiewicz K., Jarmusz M., 2017, "Envisioning urban farming for food Security during the climate change era. Vertical farm within highly urbanized areas", *IOP Conf. Ser.: Mater. Sci.*
8. Despommiers D., 2011, *The vertical farm. Feeding the world in the 21st Century*, Picador.
9. Kornbluth F., Pohl C.M., 1952, *The space merchants*, Ballantine ; Simak C. D., 1952, *City*, Gnome Press.
10. Takatsuji M., 1989, "Fundamental study of plant factories", *Plant factory*, 1, 31-47.
11. McCartney L., Lefsrud M., 2018, "Protected agriculture in extreme environments: a review of controlled environment agriculture in tropical, arid, polar, and urban locations", *Applied Engineering in agriculture*, 455-473.
12. Stapel O., 2016, "Eclairage LED dans les productions végétales de demain", Journées d'Astredhor. Morel-Chevillet P., 2019, "Cultiver sans soleil : mythe ou réalité ?", Pour, 234-235, 93-102.
13. See for example Tsouliatos D. *et al.*, 2016, "Vertical farming increases leetuce yield per unit area compared to conventional horizontal hydroponics", *Food and energy security*, 5(3), 184-191.
14. Graamans L. *et al.*, 2018, "Plant factories versus greenhouses: Comparison of resource use efficiency", *Agricultural Systems*, 160, 31-43.
15. Kikuchi Y. *et al.*, 2018, "Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan", *Journal of Cleaner Production*, 186, 703-717.
16. Morel-Chevillet G. (dir.), 2017, *Agriculteurs urbains*, Editions France Agricole.
17. Kozaï T. *et al.*, 2016, *Plant factory : an indoor vertical farming system for efficient quality food production*, chapitre 26, "Selected commercial PFALs in Japan and Taïwan", 351-386.
18. A term used for example by A. Chupin, in charge of innovation at Hrvst, a spinoff of La Florentaise, a French compagny selling soil mixes, improvers and mulches.

In Japan, plant factories put large quantities of lettuce on the market[19]. For example, the Kameoka production site was opened in Kyoto by Spread in 2007 during the first wave of investments. It currently produces 21,000 bags of salads a day, distributed under the Vegetus brand in more than 2,400 outlets. The two 16m high buildings have a footprint of 2,868 m², each with a production area of 900 m², one spread across 16 levels and the other across 12 levels, resulting in a cultivated area of 25,200 m². From the next generation of investments, the Mirai plant in Miyagi produces 10,000 salads a day in 18 towers on 6 to 15 levels, and a cover of 2,300 m², using 17,500 LED lamps. Recently, at the end of 2018, Spread launched a fully automated unit capable of producing 30,000 salads per day, intended to serve as a springboard for the Techno-Farm concept, with dozens of installations planned all over the world. The latest-generation plant factories use precision technologies, which leverage techniques developed in outdoor conventional agriculture[20], combined with the advantages of architectured environments to control variables. These smart plant factories fit in the urban planning models that the country tries to sell overseas, coined *smart communities*[21].

In North America, about 20 indoor farms were in service in 2017[22]. For example, Aerofarms markets a range of vegetable-shoots under the brand name Dream Greens. The products are grown in Newark in old industrial warehouses, in towers 6 to 10 meters high (Figure 1), and retailed by Whole Foods and the online grocer FreshDirect. In Europe, facilities are rarer. In France, Agricool grows strawberries inside containers. Instead of stacking cultivation plans, the implantation on vertical supports makes it possible to densify the plantations and to facilitate the movement of people[23]. Monoprix sells these strawberries at € 4.50 a 250g container, a price presented as comparable to organic.

These factories are therefore a reality, but their contribution to the urban food chain needs to be put into perspective. For example, in Japan, total production was estimated in 2014 at 0.6% of national production in a quite optimistic hypothesis[24], for no more than 29 hectares of production areas, a figure to compare to the 42,280 hectares of greenhouses and tunnels, and 952 ha of greenhouses with advanced environmental control[25]. In addition, production does not cover the entire cycle of the plant, from germination to maturity. Sprouts are easier to obtain than fully formed salads, if only for reasons of space and planting density. In some cases, vertical farms even serve as nurseries for conventional productions (see the case of Grafted Growers with its transplanting tomato plants).

Other crops, more profitable than salads, are conceivable in confined circumstances, starting with the therapeutic cannabis, which has been illegally cultivated with hydroponics for a long time. Another example: in Nanterre (France), the German company, InFarm, has established the production of aromatic plants in air-conditioned cabinets (80 m² on the ground), in the warehouses of Metro, a chain supplying independent restaurateurs.

3 - Huge investments, confident markets, but still many uncertainties

High-tech vertical farms require huge investments. In Japan, companies that are moving in this direction have little connection with the agricultural sector. Major electronics and energy conglomerates, such as Hitachi, Mitsubishi or Toshiba, or real estate companies, such as Fudosan, are establishing subsidiaries for their plant factory projects. Construction costs are high: "nearly 14 million euros" for Kameoka's Spread plant, "for a footprint of 2,868 m², or 4,850 € / m² of investment", a figure to be multiplied by 12 to 16 floors to obtain 25,000 m² of cultivated surface, ie "an investment of about 500 € / m² of culture"[26]. To limit costs, buildings have sometimes been repurposed. This is the case with the Fujitsu semiconductor factory at Aizu-Wakamatsu Akisai in the Fukushima area. In the rest of the world, the hundred or so companies trying out confined production are smaller. Presenting themselves as startups dedicated to "disrupting" agriculture, some manage to mobilize considerable funding: $ 226 million for Plenty, with the main contribution from a fund linked to a Japanese telecommunications group, $ 90 million for Bowery, financed by Google Ventures, 28 million euros for the last round of Agricool in France, which brought together the Public Investment Bank and some famous, innovative CEOs, etc.

Scaling up and mass production strategies are crucial for investors. For instance, the idea of developing a replicable formula, on a model of partnerships and franchises, is put forward by Plenty, which focuses in the United Arab Emirates, or Aerofarms, which targets the urban centers of North America. In contrast to this strategy of setting up large units, other players are aimed at the B2B niche of selling or leasing small-scale equipment to local restaurant or other business owners. ZipGrow, in Canada, offers a turnkey tower system. In addition to Agricool or Freight Farms, there are many initiatives to convert containers into growing units. In these various cases, equipment patents must guarantee revenue streams distinct from those derived from the marketing of produce, and those revenues should skyrocket as the modules become commonplace.

Investors and manufacturers in Japan and the United States consider vertical farms as a

Figure 1 - **Vertical farming in repurposed industrial warehouses**

Source: Aerofarms (Newark)

19. See Price J. J., 2018, "Global potential : understanding the drivers for vertical farm adoption in Asia", World Agri-tech innovation summit, for a list of the 20 bigger ones (footprint and number of salads per day).
20. Chaire AgroTIC, 2018, "Deep learning et agriculture", 49 p.
21. Henriot C. *et al.*, 2018, "Perspectives asiatiques sur les Smart Cities", *Flux*, 114.
22. Morel-Chevillet G. (dir.), *op.cit.*
23. See Beacham A.M., Vickers L.H., Monaghan J.M., 2019, "Vertical farming: a summary of approaches to growing skywards", *The Journal of Horticultural Science and Biotechnology*, 94:3, 277-283, for a presentation of such technical options.
24. Newbean Capital, 2016, *The rise of Asia indoor agriculture industry.*
25. Ministry of agriculture, fisheries and forestries of Japan, 2018, "Situation of greenhouse horticulture", february.
26. Morel-Chevillet G., 2017, *op.cit.*

future solution for food systems. Assembling various technical solutions (plant physiology, mechanics, computer science, etc.), their endeavors have to endure different reality tests over time. The examples above indicate good agronomic performance (yields, quality), economic and commercial (on-shelf availability, financing, risk assessment) and interest by the food distribution operators (consistent supplies, public opinion, traceability, etc.). But the detailed results are rarely accessible and there are contradictory signals.

Many projects have ended in bankruptcies. In the United States, the case of FarmedHere (2011-2017), the first vertical aquaponic farm (vegetables and fish) to receive the American organic label, has been widely discussed. In Europe, the liquidation of Plantagon, whose crowdfunding campaign announced aspirations of opening of 10 sites in Stockholm by 2020, shows that it is difficult to sell salads on the market at a price covering costs. In Japan, the situation is more opaque: conglomerates may assume transitional losses to ensure future positions. In addition, since 2009, massive subsidies have placed plant factories out of the market. In this country, the preference given to national production and the difficulty reforming land-use policies[27] create a specific circumstance, distorted in regards to market forces, with the various stakeholders agreeing to turn a blind eye to the real costs of production.

In regards to environmental concerns, many observers point out the contradiction between the effort made to develop green energy technology (solar panels, wind turbines), and the use of LEDs, rather than using the sun to light plants[28]. The idea of coupling renewable energies with vertical farms resembles a headlong rush into technophilia and accelerationism. Depending on the products and the situation, the relative scarcity of the various energy resources will undoubtedly determine the interest, in the coming years, of the various production options: open fields, greenhouses or vertical farms. In fact, the latter probably has a different future depending on the region or country in which it is being considered: in France there is no lack of land, but the situation is different in polder or mountain-countries like Japan, or the extreme climates found in Russia and the Middle East.

Lastly, the perceptions and behaviors of consumers remain uncertain. Regardless of the quality of produce sold in the future[29], these new farming systems challenge current socio-economic trends that call for a more natural, less technical, and less intensive agriculture. Diversely sensitive to these changes, the strategies of investors and entrepreneurs allows us to envision at least three scenarios for the future: that of the factory-line vertical farm, with a place for everyone from engineers to executives; that of a solidarist or circular economy, made of resourcefulness and mutual services around confined farms dispersed over the territory; and lastly, the scenario of a platform economy, franchising schemes that reconcile localized micro-entrepreneurship and investments by large groups. In any case, there will also be the question of how to work within these confined environments. For the moment, the visit reports show a reality made of repetitive tasks, in sometimes difficult conditions (pink light, heat and humidity, etc.) (Figure 2)[30], and the question of the impacts and benefits of automation is open to debate.

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Dreamed of and first designed in the mid-twentieth century, vertical farms for vegetables have been announced, several times, as an innovation at hand. The futuristic register prevailed, in the absence of a required template of technical and economic innovations. Today, in an increasingly urban, dense and mobile world, entrepreneurs see it as a means of simultaneously responding to several major food, environmental and logistical challenges. Projects and equipment in operation have significant areas of uncertainty: energy consumption, economic profitability, environmental standards, consumer expectations, etc. However, the many bankruptcies in this sector are not enough to invalidate business models and investor optimism, and the significant fundraising of some startups, since 2015, could even announce the beginning of a period of large-scale industrialization.

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27. Marchand R., Hofferer S., 2018, "Le développement des fermes verticales au Japon", note from the French Embassy in Japan.
28. See the critial standpoints of L. Albright et B. Bugbee, specialists in Controlled environment agriculture. Cornell University us currently working on an expertise led by N. Mattson.
29. In France, the CASDAR Techn'AU project explored this issue from the perspective of the consumer.
30. Hughes S., 2018, Vertical farming : does the economic model work?, Nuffield UK, p. 33.

Figure 2 - **Difficult working conditions**

Source: Goldstein H., 2018, « The green promise of vertical farms », IEEE Spectrum special report « Blueprints for a miracle », june. Site: Espec Mic Corp's VegetaFarm (Tokyo)

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