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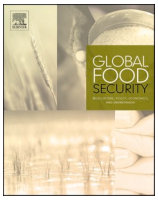

Are AgriFoodTech start-ups the new drivers of food systems transformation? An overview of the state of the art and a research agenda

Laurens Klerkx [a,b,*], Pablo Villalobos [a]

[a] Departamento de Economía Agraria, Facultad de Ciencias Agrarias, Universidad de Talca, Chile
[b] Knowledge, Technology and Innovation Group, Wageningen University, the Netherlands

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ABSTRACT

AgriFoodTech start-ups are coming to be seen as relevant players in the debate around and reality of the transformation of food systems, especially in view of emerging or already-established novel technologies (such as Artifical Intelligence, Sensors, Precision Fermentation, Robotics, Nanotechnologies, Genomics) that constitute Agriculture 4.0 and Food 4.0. However, so far, there have only been limited studies of this phenomena, which are scattered across disciplines, with no comprehensive overview of the state of the art and outlook for future research. In this paper, we argue that AgriFoodTech start-up ecosystems should receive more attention by researchers and policy makers as a relatively new, and potentially transformative, component of agrifood innovation systems, which adopt a narrative of offering a solution to the global challenges of sustainability and food security. To this end we review the extant literature and provide a brief overview of this emerging field of study, in which we sketch what constitutes an AgriFoodTech start-up, the start-up ecosystems from which they often emerge and show the potentials and pitfalls of the contribution of AgriFoodTech start-ups to food security and food systems transformation. In order to spur further research in this area, we outline four main lines for a research agenda: 1) the global geography of AgriFoodTech start-up ecosystems; 2) the role of AgriFoodTech start-ups in different food system transformation pathways and resolving food security challenges; 3) the effect of AgriFoodTech start-ups on agrifood innovation, and; 4) the influence of public policies on AgriFoodTech start-up ecosystems.

1. Introduction

In recent years, it has become obvious that food systems have reached or exceeded many of their planetary boundaries and that there is a need for radical transformation of food systems in order to achieve sustainability, create more resilient and equitable food systems and guarantee food security (Springmann et al., 2018; Willett et al., 2019). At the same time there have been many technological advances in agriculture and food systems over the past 20 years related to the 'fourth industrial revolution', such as pervasive digitalization, gene editing technologies, biotechnology, precision fermentation and molecular technologies. Some argue that these technologies can support the transformation of food systems (da Silveira et al., 2021; Herrero et al., 2020; Klerkx and Rose, 2020), an idea captured in the concepts of Agriculture 4.0 and Food 4.0. Agriculture 4.0 entails a suite of new food production technologies such as those for the transformation of protein production systems (i.e. plant-based or cultivated or cellular meat - Broad, 2020b; Lonkila and Kaljonen, 2021), digital transformation pathways that encompass digital agriculture and vertical farming and, more broadly, 'smart farming' in which all supply chain actors are connected through technologies such as sensors, the Internet of Things, platforms and block-chains (Shepherd et al., 2020; van Delden et al., 2021; Wolfert et al., 2017). Going beyond food production, Food 4.0 focuses on the processing of agricultural products. Examples of Food 4.0 technologies include genomics (personalized nutrition), functional ingredients and processing methods, food delivery platform technologies,

* Corresponding author. Departamento de Economía Agraria, Facultad de Ciencias Agrarias, Universidad de Talca, Chile; Knowledge, Technology and Innovation Group, Wageningen University, the Netherlands.
E-mail address: Laurens.Klerkx@wur.nl (L. Klerkx).

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food waste prevention, circular food economy technologies and digital technologies that enhance food traceability (Carolan, 2019; Derakhti et al., 2023; Economist Impact, 2021; Meemken et al., 2022; Rosenthal et al., 2021).[1]

There are different visions of what future food systems might look like that are underpinned by different values, and pursued by different groups of actors (Pigford et al., 2018; Zurek et al., 2021). Agriculture 4.0 and Food 4.0 represent visions of food system transformations, which put a lot of faith in advanced technologies for solving the sustainability problems of existing food systems (Klerkx and Rose, 2020). Some commentators argue that Agriculture 4.0 and Food 4.0 potentially have major positive sustainability impacts (Basso and Antle, 2020; MacPherson et al., 2022) as they can: increase the efficiency of resource use; optimize local and global food markets, and; prevent negative environmental spillovers, hence contributing to food security and the sustainability of food systems. For example, digital agriculture is seen as enabling more optimal and timely applications of fertilizers and water and a way to become more resilient to climate change and to maintain yields (Finger et al., 2019; MacPherson et al., 2022). Equally vertical farming is seen as a way to produce food close to urban populations and to reduce food miles (van Delden et al., 2021). Alternative proteins such as plant-based or cellular meat are seen as way to more efficiently use the available land, and be able to produce sufficient protein for a growing world population (Chiles et al., 2021; Lonkila and Kaljonen, 2021).

However, other commentators are more cautious about, or even reject, Agriculture 4.0 and Food 4.0, arguing that they will not fundamentally transform food systems, but will largely maintain or even reinforce current high external input systems that are dependent on fossil fuels and non-renewable resources, and the concentration of supply chains in a few powerful firms (Bronson and Sengers, 2022; Brooks, 2021; Clapp and Ruder, 2020; Galaz et al., 2021). These critics of Agriculture 4.0 and Food 4.0 typically advocate other pathways to transform food systems such as agro-ecology,[2] that are less focused on advanced biotechnological, nanotechnological, and digital technologies, but based on holistic and regenerative approaches to agriculture (Broad and Chiles, 2022; Clapp and Ruder, 2020; Fraser, 2022; Montenegro de Wit et al., 2021), changes in consumption towards more plant based diets (i.e. not based on industrialized plant-based meat alternatives, such as vegetarianism and veganism) (Lonkila and Kaljonen, 2021) and exchange mechanisms that provide an alternative to current market models, such as 'food as commons' (Guerrero Lara et al., 2023; Wickramasinghe et al., 2021).

Increasingly, there are also scholars who propose hybrid forms. An example is combining digital agriculture with agroecology. There is ongoing experimentation in this field, through concepts such as 'digital agroecology' and discussions on how to reconcile the different values underpinning this hybrid approach (Bellon-Maurel et al., 2022; Daum, 2021; Schnebelin et al., 2021; Sullivan, 2023; Wittman et al., 2020). In fact, apart from manufacturers who cater for more 'conventional' large scale farming robotics, such as John Deere, many specialized manufacturers, such as Pixelfarming Robotics or the Small Robot Company,[3] are now targeting small scale farmers and digital agroecology.

What the different forms of Agriculture 4.0 and Food 4.0 share in common is that many of the innovations in this field originate from Agtech or AgriTech and FoodTech start-ups, also referred to jointly as 'AgriFoodTech' start-ups (Vlachopoulou et al., 2021). While technological development has existed since the dawn of agriculture, the term 'Tech' has increasingly entered the discourse in recent years (Fairbairn et al., 2022; Rose et al., 2022), as the ICT and Silicon Valley related 'Tech revolution' has percolated through to other sectors, including the agrifood sector. There is now an abundance of 'Techs' such as ClimateTech (technologies to address climate change), FinTech (apps and platforms for finance and banking), and FemTech (technology aimed at improving women's health) (Hod et al., 2023; Pandey et al., 2023). The technological advances of Agriculture 4.0 and Food 4.0, which have led to the founding of start-ups to create value from emerging technologies over the past decade, has been supported by major worldwide growth of interest from global venture capital and private equity in the agrifood sector (Birner et al., 2021; Sippel, 2023).

Surprisingly, there is no unequivocal definition in the scientific literature of a start-up (Cockayne, 2019; Ehsan, 2021), but the definition provided on Wikipedia[4] is "*a company or project undertaken by an entrepreneur to seek, develop, and validate a scalable business model. While entrepreneurship includes all new businesses, including self-employment and businesses that do not intend to go public, start-ups are new businesses that intend to grow large beyond the solo founder. At the beginning, start-ups face high uncertainty and have high rates of failure, but a minority of them do go on to become successful and influential*". Though every newly founded company could be called a start-up, this paper looks at start-ups which focus on technology based products and services.

AgriFoodTech start-ups can be seen as new players in broader agricultural or agrifood innovation systems (AIS) that aim to induce new ways of innovating and new sorts of cross-sectoral networks and alliances (e.g., between agriculture and energy, agriculture and construction) drawing on integrative concepts, such as the circular and the bioeconomies (Klerkx and Begemann, 2020; Pigford et al., 2018; Weber et al., 2020). Because of their potentially disruptive technological and economic approach they are also seen as potential catalysts of transformation towards more sustainable food systems (Fichter et al., 2023; Henry et al., 2020).[5] Though they are not the only sources of innovation,[6] Agriculture 4.0 technologies, introduced by start-ups, may encourage more plant-based diets, reduce food waste, optimize the use of water, inputs and energy in agri-food systems and reduce food waste, thereby contributing to Sustainable Development Goal 12 (sustainable production and consumption). They are seen (and often presented) as a means of helping to realize food security, by improving food production and access at the local scale (for example, by developing products and services that optimize water use, reduce food waste and connect producers to consumers), as well as the global scale (e.g. by increasing transparency in global food chains and enhancing the availability of real time information to inform food policy making). Critically, they are also recognized by major international organizations, such as the World

[1] It needs to be noted that the Agriculture 4.0 and Food 4.0 concepts often overlap in terms of the technologies they encompass, and that Agriculture 4.0 is often not just centred around farm and food production but is also associated with technologies such as food processing, logistics and consumption. Similarly, related, concepts such as AgTech or AgriTech and FoodTech also have fuzzy definitions and conceptual boundaries.

[2] There are many different interpretations and narratives of regenerative agriculture (Giller et al., 2021): in their basic form they are based on productive landscapes with high crop and animal diversity, high biodiversity, non-market based exchange mechanisms, democratic knowledge production and sharing and a focus on inclusion of diverse groups (e.g. marginalized people, indigenous groups) (Bless et al., 2023).

[3] https://pixelfarmingrobotics.com/, https://www.smallrobotcompany.com/.

[4] https://en.wikipedia.org/wiki/Startup_company, visited 17-10-2023.

[5] Disruptive innovations create a new market and value network, potentially eventually displacing established market-leading firms and alliances, products and related practices (Christensen et al., 2018). For example, logistics supported by real-time quality monitoring and block chains might replace some intermediaries in the agrifood supply chain, such as clearinghouses and traders (Rijswijk et al., 2023).

[6] Other sources of agrifood innovation include public and private science organizations, grassroots movement and existing firms.

Bank, as relevant actors in agrifood innovation (World Bank, 2019, 2021).

Though the potential relevance of AgriFoodTech start-ups as drivers of innovation for food systems transformation has been identified (Herrero et al., 2020; Pigford et al., 2018; Weber et al., 2020), they have not so far been widely studied and the available studies are scattered across a range of disciplines, including economics, business and management studies, the sociologies of food and agriculture and economic geography. Hence, there is a lack of an overview of the state-of-the art of AgriFoodTech start-ups and which aspects of them merit more and deeper study, especially in relation to their potential (or one could say much hyped) contributions to food security and the transformation of food systems. From a policy perspective, more consolidated knowledge on AgriFoodTech start-ups would also be beneficial, as governments, development donors and philanthropist organizations (such as World Bank, FAO, the Bezos Earth Fund and the Bill and Melinda Gates Foundation) as well as national and international research and innovation organizations (such the CGIAR) are increasingly engaging with AgriFoodTech start-ups and see them as potentially important players in addressing sustainability and food security issues and supporting the transformation of food systems. This is where this perspective paper aims to make a contribution, by providing a brief overview of this emerging field of study and outlining lines for a research agenda.[7]

2. Overview of the state of the art

In this section, we briefly explain what AgriFoodTech start-ups and start-up ecosystems look like, before describing how the literature reports on how they (potentially) contribute to food security and the transformation of food systems.

2.1. What constitutes an AgriFoodTech start-up and start-up ecosystem?

AgriFoodTech start-ups come in many shapes and sizes. They may target end-users, such as farmers and consumers, or other actors in food supply chains, such as traders and food manufacturers. Some of them are oriented towards primary production, and aim to develop and offer services such as real-time soil and weather monitoring through sensors, more targeted and crop management, automating production (through robots for seeding, weeding, milking and harvesting) and platforms using apps and social media to engage on markets for goods and information, e.g. to sell produce, obtain advice, etc. (Baumüller, 2017; Herrero et al., 2020). They may also be aimed at identifying new ingredients for food products and new ways of marketing food (e.g. delivery apps that connect producers and consumers) (Carolan, 2019; Meemken et al., 2022). Box 1 provides some examples of start-ups and more mature firms which have been developed following a Tech start-up philosophy.[8]

While some start-up founders may come from an agricultural or food background, Tech entrepreneurs from other sectors (such as information technology) also often enter the agri-food sector without much previous knowledge of, or experience with it (Fairbairn et al., 2022; Sippel and Dolinga, 2023). Often, founders of AgriFoodTech start-ups are students or recent university graduates or researchers who want to create a commercial or societal impact from a scientific discovery or invention. At the same time there are also, more seasoned, 'serial entrepreneurs' who have already created successful businesses and initiated new start-ups. Often, the founders proclaim that they want to transform food systems and make them more sustainable, secure future food supply under pressures such as climate change or end cruelty towards animals (Broad, 2020a; Fairbairn and Guthman, 2020; Fairbairn et al., 2022; Reisman, 2021; Sexton, 2018). Start-ups are found to have a marked entrepreneurial spirit and culture, characterized by informality, flexibility, and horizontality, but that this is accompanied by high levels of stress, hard work, and a culture of taking the initiative and individual responsibility (Cockayne, 2019; Fairbairn et al., 2022) .

Start-ups typically emerge within AgriFoodTech start-up ecosystems, which provide physical spaces for start-ups to work (these are often close to and closely linked with universities and research or business centres) and provide support facilities (Birner et al., 2021; Lachman and López, 2022; Mikhailov et al., 2021; Wolfert et al., 2023). These spaces and support facilities go by names such as seed beds, incubators, accelerators or science and technology parks, and are connected to different public and private organizations (universities, government programmes, science parks, in-house incubators of large firms, etc.). Box 2 provides some examples of support actors active in the agrifood sector. As can be seen in this box, some support actors, such as incubators, investment brokers and research organizations focus on a specific region or a specific technology (e.g. robotics). Others are broader in scope, either supporting several sorts of AgriFoodTech start-ups, or having several regional branches under the same banner and operating globally, thus having a wider potential significance. Some are public-private and independent, whereas others are closely tied to existing large agrifood companies. Some are also third sector actors, like the World Wildlife Fund (WWF), acting as impact investors. Alongside these incubators and investment brokers, there are also both regional and global networking events where investors and start-ups can connect with each other, and where so-called 'AgriFoodTech influencers' (Klerkx, 2021), who signal trends and can help to create a buzz for particular technologies, are present.

AgriFoodTech start-up ecosystems offer support for the pre-emergence, emergence and post-emergence stages of start-ups: founding a business, developing the ideas and assessing their viability, finding partners and investors, organizing R&D and product development, developing a business proposition and model, identifying markets, doing marketing, valuation, de-risking investment and providing regulatory support (e.g. in regard to patenting and product approval) (Kansheba and Wald, 2020; Mungila Hillemane et al., 2019; Moro-Visconti, 2021; Newell et al., 2021). Finance for the set-up and development of start-ups may come from either governmental bodies and venture and private equity capital firms (or both), the latter of which raise private capital and then channel it into start-ups on behalf of their investors (such as pension funds, university endowments or insurance companies) (Gonzalez-Uribe and Leatherbee, 2018; Sippel and Dolinga, 2023; Stephens and Wolf, 2023). Often there are different rounds of funding (called pre-seed, seed, series A, B, C, D, E, F). After an incubation phase, a phase of growth or scale-up starts in which companies grow further in terms of size and market scope (Mohammadi and Sakhteh, 2023). Frequently start-ups do not succeed in crossing the so-called 'valley of death' and creating a viable product and break-even and will cease to exist (Gbadegeshin et al., 2022). Though it is hard to exactly pinpoint when a start-up ceases to be a start-up and becomes a scale-up and eventually a 'normal' company, it is often considered that can be said to be when a start-up has been in business for more than 3 years and/or has more than 50 employees (Cockayne, 2019).

Though start-ups can be focused on a national market and national challenges, they often have an ambition to become international. The venture capital and private equity investments on which they often draw are highly international, and so encourage this perspective among AgriFoodTech start-ups (Fairbairn et al., 2022; Sippel and Dolinga, 2023). They can be influential in steering local start-ups and local

[7] The overview presented in this section is based on an exploratory review, achieved by searching in the comprehensive scientific database, Scopus, using keywords such as 'Agriculture 4.0', 'Food 4.0', 'start-ups', 'AgTech', 'AgriTech', 'FoodTech', A snowball method was then employed, following through on the references in the articles found. This review was not comprehensive and systematic, which would have been beyond the scope (and resources) of the research underpinning this paper.

[8] For overviews of Agrifoodtech start-ups, see also https://forwardfooding.com/foodtech500/, and www.agfunder.com. Some interesting case studies can be found in Broad (2020a); Daum et al. (2021); Fairbairn et al. (2022); Lenain et al. (2021); WorldBank (2021).

Box 1
Examples of AgriFoodTech start-ups (some of which have grown to scale) and the country where they were initially founded

Vertical farming

AeroFarms (United States), Square Roots (United States), AgroUrbana (Chile).

Plant-based protein

Impossible Foods (United States), The Vegetarian Butcher (the Netherlands), Those Vegan Cowboys (the Netherlands), Wild Type Foods (United States), NotCo (Chile).

Agricultural robotics

Small Robot Company (United Kingdom), Pixel Farming Robotics (the Netherlands), SwarmFarm (Australia).

Agricultural product and services platforms.

AgroSmart (Brazil), Hello Tractor (Nigeria), Agroconsultas (Argentina), AgroMatch (Chile).

Box 2
Some examples of AgriFoodTech start-up innovation ecosystem support actors

Incubator and accelerator programmes and ecosystem builders

Connected to large private (international) agrifood companies: Bayer Leaps, Lely Feed The Future, John Deere Startup Collaborator, BASF Start-up Science, Shoots by Syngenta, Deloitte FoodTech Accelerator, Pascual Mylkcubator 2.0, Danone Manifesto Ventures, The Unilever Foundry, Nutreco Feed and Food Challenge, Mondelez Co-Lab Tech.

National or regional public or public-private incubator programs and ecosystem builders: Thrive Canada Accelerator (Canada), Zone AgTech (Canada), British Columbia Centre for AgriTech innovation (Canada), Nature Growth (Israel), The Kitchen Hub (Israel), Fresh Start (Israel), Wageningen University and Research Start Hub (The Netherlands), Robocrops (The Netherlands), AgFrontier (Australia), SproutX (Australia), Beanstalk AgTech (Australia), Acre Agtech Incubator (United States), AgLaunch (United States), Farm 491 (United Kingdom), AgriTech-e (United Kingdom), Italian National Agritech Centre (Italy), FoodTech HUB Latam (Brazil), India Agritech Incubation Network (India), Dao Foods (China), The Yield Lab Europe (Europe), The Yield Lab Latin America (Latin America), The Yield Lab Asia (Asia) RootCamp (Germany), Foodtech.ac (Poland), EIT Food (Europe), IICA Semana de la Agricultura Digital (Latin America), FAO Innovation Fund Incubator (global), UNDP CULTIV@TE (global), CGIAR Accelerate for Impact Forum (global), Endeavor (global).

Networking and matchmaking events

EvokeAg (Australia), World Agri-Tech Innovation Summit (global, in multiple countries), F&A Next (Netherlands), Agrifood Tech Expo Asia (Singapore), AgTech Connect (United States), AgTech Nexus (United States), Farm & Food 4.0 (Germany), CFIAgrotech (Chile).

Investment brokers/venture capital and private equity firms

AgFunder (global), Tenacious Ventures (Australia), S2G ventures (United States), Bread and Butter Ventures (United States), Syngenta Ventures (global), Rockstart Ventures (Netherlands), Global AgInvesting (United States), AgLaunch (United States), Rabobank FoodBytes (The Netherlands), WWF Impact Investing (global).

Specialized research and innovation institutes and programmes

Delft AgTech Institute (Netherlands), Digital AgriHubs (Europe), CARE-AI (Canada), Agriculture Technology Campus (United States), Agritech Institute for Small Farms (United States), Cornell AgriTech (United States), Global Institute for AgriTech economics (United Kingdom), NUS Agritech Centre (Singapore), Good Food Institute (United States).

AgriFood tech media, advisors and influencers

AgFunder (Global), AgThentic (Australia), Agtech So What (Australia), Green Queen Media (Singapore), Good Food Institute (United States), Agritecture (United States), Future of Agriculture (United States).

innovation ecosystems towards developing 'investable ideas' that have a more global potential. In this they are aware of international trends and can bring in international expertise to stimulate such an expansion of ambitions (Fairbairn et al., 2022; Sippel, 2023). AgriFoodTech start-up ecosystems often follow the Silicon Valley model in terms of their set-up, entrepreneurial values and the discourse and terminology they employ (Broad, 2020a; Fairbairn and Guthman, 2020; Fairbairn et al., 2022; Klerkx and Rose, 2020; Sexton, 2020). At the same time they do emerge in the particular 'innovation culture' of their country or region, hence the Silicon Valley model may not be universally applicable (Pfotenhauer and Jasanoff, 2017a, 2017b).[9]

[9] Due to linguistic bias this box is biased towards organizations that present themselves in English. As such, this is a not an exhaustive list of examples. For more details of incubators and accelerators see https://medium.com/mudcake/the-a-z-of-foodtech-incubators-accelerators-grants-df1d154029fa, https://incubatorlist.com/top-agriculture-startup-accelerators-incubators-and-vcs/, https://www.failory.com/startups/agtech-accelerators-incubators, and for investment firms see https://agfundernews.com/who-were-the-most-active-food-and-agriculture-technology-venture-capital-firms-in-2022.

2.2. How AgriFoodTech start-ups might contribute to food security and the transformation of food systems

Start-ups often have the intention of disrupting existing and dominant systems, and to introduce innovations that may radically change the way a market, sector, or system operates. They largely do this by scaling their product and services and becoming established players, sometimes outcompeting and replacing existing firms. Nonetheless, in their pathway to growth they often engage with established players, whilst being their competitors. Many existing firms in the agrifood sector actively work with AgriFoodTech start-ups, finance them, or have in-house incubators (Birner et al., 2021; Mungila Hillemane et al., 2019). Examples include: the milking robotics multinational, Lely Systems; the agrifood bank, Rabobank; the multinational agrochemical company, Bayer and the meat company, AgroSuper in Chile (see also box 2)[10]. Such corporate venturing is a way for existing firms to foster 'organizational ambidexterity', using start-ups as a space for experimenting and explorative innovation (more radical innovations), while other parts of the company can continue with exploitative innovations (to optimize current systems) until the start-up's innovations have reached sufficient maturity to be absorbed by the incumbent (Lo and Theodoraki, 2021; Rossi et al., 2020; Sauberschwarz et al., 2022). The lean and agile processes that start-ups use to innovate can also induce changes in the structural and institutional innovation set-ups of existing firms (Sraml Gonzalez and Gulbrandsen, 2021). The novel technologies that AgriFoodTech start-ups work on (Herrero et al., 2020), and the hybrids they can create between different systems (within agriculture, e.g. digital agro-ecology, circular food systems) and between agriculture and other sectors (e.g. the energy sector through agri-voltaics), may also induce new ways of cross-sector interaction (Andersen and Markard, 2020; Klerkx and Begemann, 2020) or what has been called 'industry convergence' (Rennings et al., 2023), which may produce novel combinations.

It is argued that start-ups have a clear potential contribution to make to food security (e.g., by providing tools and services to enhance pest management, optimize food trade flows and crop planning, mitigate climate change effects), meeting broader food system sustainability goals (i.e. those embedded in the Sustainable Development Goals), and the transformation of economic sectors (such as the agrifood sector) (Fichter et al., 2023; Henry et al., 2020; Herrero et al., 2021; Lüdeke--Freund, 2020; Navarro and Camusso, 2023; Romme et al., 2023). It is argued that new players in innovation ecosystems, such as AgriFoodTech start-ups, are often motivated by 'transformative innovation missions' (Klerkx and Begemann, 2020), i.e. targeted challenge-led innovations that contribute to the transformation of food systems. Drawing on sustainability transition studies, Horne and Fichter (2022) state that start-ups may form part of socio-technical niches (experimental innovation spaces), which can transform existing industries and sectors (referred to as the socio-technical regime), and thereby help overcome the pathway lock-in of incumbent food systems (Conti et al., 2021). However, given the dynamic and volatile nature of many start-ups, it is difficult to assess the contribution that they actually make to meeting sustainability goals. As such it has been argued that "it seems more fruitful to assess the prospective and not only the current sustainability impacts of new ventures, due to the different characteristics of these young companies" (Fichter et al., 2023: p.3). Often, start-ups will only start to have real impacts after they have become established firms with a functional product or service and customer base, and have reached a certain scale.

2.3. Ambitions and impact of AgriFoodTech start-ups with regard to food security and the transformation of food systems

Start-ups often use pitches: condensed narratives, proclaiming a value proposition and the societal and environmental sustainability contribution that they aim to make (Varas et al., 2023). The way that AgriFoodTech start-ups position themselves (in terms of their transformative ambitions with regards to sustainability and food security) has so far mostly been studied mainly through the lens of critical agriculture and food sociology and science and technology studies (Biltekoff and Guthman, 2022; Broad, 2020a; Carolan, 2017, 2020a, 2020b; Fairbairn and Guthman, 2020; Fairbairn et al., 2022; Guthman and Butler, 2023; Miles and Smith, 2015; Schneider, 2018; Sippel and Dolinga, 2023; Duncan et al., 2021; Rose et al., 2022; Stephens and Wolf, 2023). These studies tend to be sceptical of the claims that these start ups make citing four main reasons why they may fall short of their ambitions:.

1. Their ambitions may be high but these are curbed by global venture capitalist and private equity requirements for return on investment and hence the ambitions may be toned-down as the start-up develops.
2. They invoke grand sustainability challenges or images of food system collapse and the essential role of their product or services in ensuring food security, but these are mainly to attract capital and are not always authentic or present overly simplistic 'techno-fixes' or 'tech-solutionism' which do not acknowledge the complexity of transforming food systems or achieving food security.
3. They use a sustainability discourse, such as regenerative agriculture, but the solutions mainly support business as usual and are a form of green-washing, and enhance further financialization of food systems.
4. The 'newness', 'disruptiveness' or 'radicalism' of the solutions proposed is sometimes exaggerated as they turn out to be incremental improvements of existing systems or the solution to the problem can also be achieved without high-tech solutions.

Nonetheless, this does not preclude that there are AgriFoodTech start-ups which are genuine in their sustainability goals and principles, and some start-ups are genuinely driven by social and environmental motives (Horne and Fichter, 2022; Kuckertz et al., 2019; Navarro and Camusso, 2023; Stephens and Wolf, 2023; Wittman et al., 2020). These AgriFoodTech start-ups may well seek ways to create hybrids between different future pathways to transform food systems (e.g. digital agro-ecology) and overcome the apparent dichotomy between 'high-tech' and 'low-tech', or 'alternative', food systems (Newell et al., 2021; Sullivan, 2023).

3. Research agenda

As has become clear from the overview presented in section 2, AgriFoodTech start-ups and start-up ecosystems as well as their potential role in the transformation of food systems have already received scientific attention. However, the field of study is still dispersed, has certain geographical biases and the scope and size of empirical evidence regarding how much such start-ups actually contribute to food security and the transformation of food systems is still limited. In this section we present a research agenda with four research lines which would expand and consolidate this field and may provide practical insights to policy makers on how to foster AgriFoodTech ecosystems in order to support food security and the transformation of food systems.

3.1. The global geography of AgriFoodTech ecosystems

Investment brokers and AgriFoodTech media, such as AgFunder,

[10] https://feedthefuture.io/, https://www.agrosuper.cl/innovacion-abierta/, https://leaps.bayer.com/, https://www.foodbytesworld.com/.

regularly publish maps of AgriFoodTech start-ups in particular regions.[11] However, more in-depth scientific studies looking at the dynamics of the AgriFoodTech ecosystem (such as investment, business models and collaboration patters, mergers and acquisitions) are scant and have a geographical bias towards the state of California in the United States of America (Biltekoff and Guthman, 2022; Fairbairn and Guthman, 2020; Fairbairn et al., 2022; Mikhailov et al., 2021) with some work emerging work in relation to Australia (Sippel, 2023), Canada (Newell et al., 2021) and Latin America (Clemente Rincón, 2020; Lachman and López, 2022; Lachman et al., 2022). There seems to be less published scientific literature about what is happening in Europe, Africa and Asia, although some studies do allude to AgriFoodTech start-up ecosystems in these places (Daum et al., 2021; Goswami et al., 2023; Wolfert et al., 2023). Thus, the current picture of AgriFoodTech ecosystems in different locations and how these start-up ecosystems are connected via knowledge and capital flows is incomplete.

Future studies could build on initial classifications of AgriFoodTech business models and ecosystem configurations (Birner et al., 2021; Newell et al., 2021; Phillips et al., 2019; Wolfert et al., 2023) to arrive at more robust knowledge of what business models exist globally (including those based on inclusive business models or social entrepreneurship), how universal or locally specific AgriFoodTech systems are (Miles and Smith, 2015; Sexton, 2020), and how they compare from region to region. This should include the nature of regional or national public and private support organizations, but also the role of international spaces for networking, mentoring and the procurement of capital (such as those mentioned in Box 1). Concrete research questions in this line hence could include:

- What do AgriFoodTech start-up ecosystems look like in different parts of the world in terms of the profiles of their founders and the coherence and consistency of public and private support instruments, such as incubators and accelerators?
- What sort of Agriculture 4.0 and Food 4.0 technologies do AgriFoodTech start-up ecosystems focus on in different countries? Are there particular hotspots for particular technologies?
- How do indicators, such as the level and source of investments, number of new start-ups, ratio of successful market launches and failures, procurement by incumbents, compare across regions?
- What are the global connections between AgriFoodTech start-up ecosystems in different countries, in terms of knowledge and finance flows?
- Have local variations of the Silicon Valley start-up model emerged in AgriFoodTech start-up ecosystems (in terms of incubating, mentoring, de-risking, etc.) and what do these look like?
- How do different AgriFoodTech start-up ecosystems differ in terms of the sort of investors they attract?
- What is the role of AgriFoodTech media, advisors and influencers, as well as globally active incubators (such as YieldLab or Endeavor which have activity in different regions – see Box 2), in shaping local and global AgriFoodTech start-up ecosystems?

Methodologically, data science methods such as Big Data analysis or machine learning, based on investment and patent data, and publicly available profiles of companies and incubators on the internet and in databases, such as Crunchbase, may be of value in mapping and comparing Agrifoodtech start-up ecosystems. Also, structural analysis of AgriFoodTech start-up ecosystems combining insights from start-up literature (Mohammadi and Sakhteh, 2023; Newell et al., 2021) and AIS studies (Eastwood et al., 2017; Klerkx and Begemann, 2020) could be fruitful. In terms of finance flows, this could follow approaches from critical agrarian sociology on financialization (Sippel, 2023; Sippel and Dolinga, 2023), and perspectives on impact or transformative investment (Mikolajczyk et al., 2021; Penna et al., 2023).

3.2. The effect of AgriFoodTech start-ups on agrifood innovation

AgriFoodTech startups are seen as a new player in AIS (Klerkx and Begemann, 2020; Weber et al., 2020), and one important area to explore is how start-ups interact with farmers in their innovation processes (von Veltheim and Heise, 2020). On the one hand, AgriFoodTech start-ups coming from other sectors may have limited understanding of agriculture and food, and especially how the agrifood sector deals with risk and temporality (e.g. working with agricultural production cycles and seasonality and long term ecological processes, food security and food safety issues). On the other hand, given the agile innovation paradigms that they typically follow, they may adopt other ways of doing on-farm experimentation with farmers, e.g. through data and machine-learning enabled experimentation (digital twins) (Lacoste et al., 2022; Verdouw et al., 2021). Hence, following Cockayne (2019), conceptual and theoretical development would be needed on what constitutes an AgriFoodTech start-up and whether their way of innovating differs from start-ups in other sectors. Also, despite some initial work on business models (Birner et al., 2021; Phillips et al., 2019; Vlachopoulou et al., 2021), it is needed to further explore what sorts of business models start-ups introduce to implement their innovations, if they actually work for farmers and other agrifood sector actors, and how effective they are in different contexts (e.g. smallholder versus large scale farmers and low versus high income countries).

AgriFoodTech start-up ecosystems are part of broader AIS which include multiple actors (Eastwood et al., 2017; Wolfert et al., 2023), such as large firms, cooperatives, research institutes and agricultural advisors. Start-ups interact with or are connected to these actors (Birner et al., 2021; Rijswijk et al., 2019; Schnebelin et al., 2021), but it is as yet not well understood whether, and how, they change the process of agrifood innovation through their collaboration with established research institutes and existing firms (which also increasingly describe themselves using terms such as AgTech and FoodTech). It is also relatively unknown how they connect to third sector actors (such as NGOs and philanthropic organizations) and vice versa. Hence, there is a need to study how these start-ups affect innovation processes and routines in AIS (Klerkx and Begemann, 2020; Newell et al., 2021). Such an understanding is important, as it would help to better channel public and private funding towards food system transformation goals and enhance productive collaborations.

In this line of work, questions to explore include:

- How does the particular context of the agrifood sector impact on or change the typical start-up development process (in terms of time frames, maturity of innovations before their launch, risk perceptions, etc.)?
- What are the motivations, strategies and practices of corporate venturing from the side of both AgriFoodTech start-ups and existing firms?
- How does interaction of AgriFoodTech start-ups with existing firms influence the ability to get scalable products and services beyond seed funding stage?
- Does cross-sector learning through AgriFoodTech start-ups take place? And, if so, how?
- How do AgriFoodTech start-ups engage and experiment with farmers and other agrifood system actors to create appropriate products and services?
- What sorts of AgriFoodTech start-up business models have emerged that function in the specific context of the agrifood sector?

[11] https://agfundernews.com/market-map-charting-the-next-wave-of-agtech-value-for-farmers, https://agfunder.com/research/europe-2022-Agrifoodtech-investment-report/, https://agfunder.com/research/latin-america-Agrifoodtech-investment-report-2023/.

- Do AgriFoodTech start-ups change the way agrifood research and extension is done, and more broadly the dynamics in AIS? And if so how?

These sorts of questions can be explored through qualitative methods, such as interviews, ethnographic work based on participant observation and work shadowing, as well as discourse analysis and institutional analysis, as applied in disciplines such as agrarian sociology, business and management studies, and agricultural science, innovation and technology studies (Fairbairn et al., 2022; Annosi et al., 2023; Sippel and Dolinga, 2023). Quantitative approaches from economics and management studies (such as studies on market configurations and investment patterns), and social network analysis can shed light on what sorts of new innovation configurations emerge in AIS (see e.g. Birner et al., 2021; Newell et al., 2021; Mori-Visconti, 2021), and what sorts of business ecosystems are an outcome (Coskun-Setirek et al., 2023).

3.3. *The role of AgriFoodTech start-ups in different food systems transformation pathways and effects on food security outcomes*

Though there is an emerging body of work on how AgriFoodTech start-ups position themselves in terms of food security and the transformation of food systems (Fairbairn and Guthman, 2020; Fairbairn et al., 2022), there is still a need for a better understanding of the diversity of transformation pathways that AgriFoodTech start-ups pursue. It is also needed to study where clear clusters of similar technological solutions or social value propositions form and scale-up and consolidation takes place (Klerkx and Begemann, 2020; Navarro and Camusso, 2023). Here, it is important to consider whether different products and services offered by AgriFoodTech start-ups leads to the 'bundling' of innovations (Barrett et al., 2020) to achieve particular pathways of food system transformation, and how particular transformation pathways grow or shrink in view of hype cycles and competition with other transformation pathways.

Another important issue to assess is whether and how start-ups within Agriculture 4.0 and Food 4.0 engage with paradigms such as regenerative agriculture or agroecology, which are seen as less 'high tech', and to what extent such engagement is genuine or mere greenwashing? In other words, following arguments from critical agrarian sociology (Fairbairn et al., 2022; Sippel and Dolinga, 2023) are these like the 'Emperor's New Clothes', in which these narratives sound aspirational but are underpinned by little more than normal capitalist goals for the new company and its investors?[12] Understanding the diversity of transformation pathways also includes investigating the investment patterns and the motives of investors (quick returns on investment, or rather impactful and transformative investment driven by alternative economic models?). As well as looking at investment, it important to assess the role that start-up ecosystems as a whole play in terms of stimulating or hindering an orientation towards sustainability and contributing to food security and food system transformation (which links to research line 1). Lastly, there needs to be a better understanding of the what long term effects that the disruptive propositions of start-ups may have on existing agriculture and food sectors, in terms of production and consumption and as well as in terms of justice (who benefits and who loses, how does it affect access to nutritious food, etc. ?). Such research has recently been done on topics such as protein production and digital agriculture (Helliwell and Burton, 2021; Metta et al., 2022). This would also imply a deeper analysis of how the start-up and scale-up process is supported and regulated (see also research line 4), and also how future entrepreneurs might be formed and how they envision their role in food system transformation and the business ethics that underpin their actions (Fairbairn and Guthman, 2020; Fairbairn et al., 2022; Ryan et al., 2023; Yoon et al., 2021).

In view of the above, future studies could explore the following questions:

- How do AgriFoodTech start-ups envision the contribution of that their technology will make to sustainability and food security?
- What is the larger food security and food system transformation vision that AgriFoodTech start-ups espouse?
- How much substance is there to the sustainability ambitions proclaimed by AgriFoodTech start-ups and influencers and investment brokers through the imagery and language that they employ?
- How congruent are business models of AgriFoodTech start-ups in relation to issues related to ethics, sustainability and social inclusion?
- How do AgriFoodTech start-ups combine their ambition for growth with developing locally specific solutions?
- How does the background of founders influence how AgriFoodTech start-ups engage with the transformation of food systems and food security?
- For example, in terms of gender, ethnicity, education, social class, previous experience, rural or urban background?
- How do these founders navigate the tensions surrounding their sustainability ambitions and business ethics in relation to the expectations of a quick return on investment?
- What is the influence of investors on AgriFoodTech start-ups' ambitions to realize food security and the transformation of food systems?
- To what extent do AgriFoodTech start-ups change the status quo in food systems, in terms of the position and power of existing and dominant actors?
- What are the combined effects of different AgriFoodTech start-ups' products and services in view of achieving food security and the transformation of food system through bundled innovations and scaling efforts?
- Are the technology-oriented solutions of AgriFoodTech start-ups complemented by social, institutional and regulatory innovations? And how?
- How do AgriFoodTech start-ups navigate the rise and fall of interest in their product or concept in view of cycles of hype and disillusionment?

When thinking of the methods and techniques required to explore these questions, it could be fruitful to assess how elements of start-ups' ambitions and their actual product or service map against food security and food systems sustainability and transformation frameworks (Hebinck et al., 2021; Herrero et al., 2021). The perspectives of transition and transformation studies, such as the multi-level perspective on socio-technical transitions (Fichter et al., 2023; Stephens and Wolf, 2023), mission-oriented agricultural or agrifood innovation systems (Klerkx et al., 2023; Klerkx and Begemann, 2020) and scaling-readiness (Sartas et al., 2020) or balanced readiness level assessment (Vik et al., 2021), could help us to understand the broader systemic and cumulative contribution of start-ups to the transformation of food systems, especially during the process of scaling-up. Longitudinal analysis (ex-durante and ex-post) or scenario analysis (ex-ante) through modelling could shed light on whether such food security or food systems transformation ambitions actually have sustained effects. Approaches such as responsible innovation (Chiles et al., 2021; Klerkx and Rose, 2020; Ryan et al., 2023) could also be useful in addressing concerns around power imbalances and industry concentration in processes of innovation and scaling, as well as the risk of moving towards 'one-size-fits-all' solutions (Pfotenhauer et al., 2021; Wigboldus et al., 2016).

[12] We thank one of the reviewers for providing this metaphor.

3.4. The functioning and impact of public policies for transformative AgriFoodTech innovation

As a fourth line of research, we propose the study and analysis of the effects of science, technology, entrepreneurship and innovation policies on the development of AgriFoodTech start-up ecosystems and their contribution to food security and the transformation of food systems. It is widely recognized that public policies can enhance start-up ecosystems through, for example, the funding of incubators and accelerators, and by providing risk-capital (Audretsch et al., 2020). However, in line with criticisms that AgriFoodTech may actually reinforce current 'broken' food systems (Fairbairn and Guthman, 2020; Fairbairn et al., 2022), this would call for a critical policy capacity that would enhance the engagement of transformative or mission-oriented innovation policy with AgriFoodTech start-up ecosystems (Fichter et al., 2023; Stephens and Wolf, 2023). Such transformative or mission-oriented innovation policy is about challenge-led innovation for the transformation of food systems and implies strong orchestration from the public sector (Klerkx and Begemann, 2020). While AgriFoodTech start-ups may play key roles in this, this may also conflict with the typical start-up philosophy of unbounded entrepreneurship and technology-oriented solutions. We believe that this type of research would allow the monitoring and evaluation of whether and how policies are capable of redirecting innovation culture to encourage the creation and consolidation of start-ups that genuinely contribute to developing sustainable food systems.

In this line of research, the following questions could be asked:

- How does public funding for AgriFoodTech start-ups differ from private funding in terms of the problems it aims to solve and the sorts of solutions it supports?
- What particular policies do different countries have with regards to supporting AgriFoodTech start-ups, particularly in view of addressing food security and food system transformation challenges?
- What degree of steering towards certain, preferred, food system transformation pathways do policies for AgriFoodTech start-up ecosystems provide?
- How do AgriFoodTech start-ups exercise political power and influence policies in their favour? And through what mechanisms?

This line of work can benefit from theories and methods from policy evaluation studies and political science, as well as broader mission-oriented innovation systems frameworks, such as analysis of policy mixes, assessment of public investment, and analysis of policy discourse (Kok and Klerkx, 2023; Rogge and Reichardt, 2016).

4. Conclusions

The aim of this paper is to better position AgriFoodTech start-ups on the radar of the broader scientific community. We believe that they are still relatively understudied and perhaps also underrated players in agrifood innovation systems and the transformation of food systems. Therefore, as yet, it is still not possible to conclusively answer the question that forms the title of this paper, "Are AgriFoodTech start ups the new drivers of food systems transformation?".

In order to answer this question, the paper shows that there is a need to better understand:

- the composition and diversity of AgriFoodTech start-up ecosystems in different countries and how they are interconnected;
- the way AgriFoodTech start-up ecosystems change how agri-food innovation is organised and how they are embedded in agrifood innovation systems;
- the promises and realities, as well as pitfalls, caveats and trade-offs in regards to AgriFoodTech start-ups' contributions to food security and different food systems transformation pathways, and;
- how policy supports or inhibits AgriFoodTech start-up ecosystems to achieve food security and the transformation of food systems.

Given the different dimensions of this agenda, such research will need to be both qualitative and quantitative, and draw on multiple disciplines. There is much scope for applying theories and methods from disciplines including agricultural economics and sociology, agri-food science, innovation and technology studies, management science, policy studies, behavioural psychology and transition and transformation science to explore the research lines and questions outlined above. Besides interdisciplinary studies, there is also scope for transdisciplinary work, in which researchers work together with AgriFoodTech start-ups seeking to tailor their technologies to farming practice and other food system activities and processes through co-design, and enhancing the bundling of innovations to better support food system transformation pathways.

Deeper insights into the pros and cons of AgriFoodTech start-ups and start-up ecosystems may help guide policy makers and investors, to avoid that they hop on a 'disruptive tech hype bandwagon'. A broader range of studies into AgriFoodTech start-ups and start-up ecosystems can support realistic and evidence-informed policies so as to optimally use the potential of AgriFoodTech start-ups to support the transformation of food systems.

Declaration of competing interest

The authors report no conflict of interest.

Data availability

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