REVIEW
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Technological Innovation and Agrifood Systems Resilience: The Potential and Perils of Three Different Strategies

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The interest in technological innovation has burgeoned in recent years. Theory and research support the vital role of innovative technologies in enhancing agrifood systems resilience. In this theoretical contribution, focusing on different sets of technologies, we present three technological innovation strategies, discuss their potential for strengthening resilience, and expose some open issues that need to be addressed. Responsible technological innovation arose as a response to the growing concerns about the possible unintended impacts of mega-technological trends, like digital farming tools or nanotechnologies, on agrifood systems. Although responsibly innovating is far from easy, and despite the gaps between theoretical ideals and innovation praxis, responsible technological innovation is a promising development since it can prevent counterintuitive effects of technologies on resilience. On the other hand, poly-innovation emerged as a social practice in which internetworking technologies facilitate—and create bundles with—organizational, social, and business innovation. In that strategy, technology represents a mediator of resilience-enhancing social behavior. However, by promoting the uberization of agrifood systems, poly-innovation is associated with various uncertainties. Finally, micro-innovation refers to the incremental adaptations of existing technologies or the development of new ones through bricolage and tinkering. The commercialization of such innovations through open design can increase the resilience of small-scale farming, especially in low-income countries. Nonetheless, the lack of financial resources, technical assistance, and institutional support hamper the full exploitation of micro-innovation.

Keywords: innovation, agrifood systems, technology, micro-innovation, social innovation, poly-innovation, resilience, responsible innovation

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INTRODUCTION

Agrifood systems resilience is a hot research topic and policy theme. Scholars associate the resilience of agrifood systems with various challenging problems, such as climate change (Zougmoré et al., 2021), public health crises (Klassen and Murphy, 2020), nutrition security (Kahiluoto, 2020), food waste (BajŽelj et al., 2020), and rural poverty (Dixon et al., 2021). Policy documents also highlight the importance of promoting agrifood systems resilience. After the emergence of the COVID-19 crisis, the European Commission (2020) emphasized the need to build up more resilient farming systems, which should be recreated under conditions of diversity. Before the pandemic, the European Commission (2018) had called for a targeted common agricultural policy with the purpose of supporting resilient farming activities. Other organizations (OECD, 2021; OECD/FAO., 2021) also advocate the idea of paying attention to agroecosystems resilience, enhancing in parallel social resilience.

However, what does resilience mean for agrifood systems? According to Walker et al. (2004), resilience refers to a systems' capacity to absorb changes and adjust through reorganizing itself when experiencing disruptive changes. Such an ability allows the system to maintain its functions and retain its identity while experiencing disturbances and changes in its external environment. The two types of resilience usually discussed in the literature are "engineering" and "ecological" resilience. The first one refers to the ability of a system to return to a steady state after experiencing external stresses or disturbances, hence presupposing the existence of an equilibrium. The ecological view of resilience, which we accept in this article, endorses the existence of multiple equilibria, the dynamic interrelations between systems' elements and speaks of a system's ability to reach an alternative equilibrium, even by changing structure but without losing its essential functions (Folke, 2006; De Weijer, 2013; Lorenz, 2013; Doherty et al., 2019). In this vein, resilience concerns the relationship between a system, its properties, and the external environment. As Lorenz (2013, p. 10) aptly puts it, "resilience is a relational concept that saliently marks the importance of a balanced relation between a system and its environment, as well as their seminal adjustment with regard to the system's persistence in the future." Future is a key term in this respect. Resilience is a property permitting any system to approach a sustainable future by rebounding, resisting, and adapting when needed (Folke, 2006) and by increasing its ability to face ongoing changes (Madni et al., 2020).

To better understand the concept of agrifood systems resilience, it is pivotal to consider their structure(s) and properties. The human-nature couplings that emerge within such complex configurations define the qualities of agrifood systems, giving them the attributes of social-ecological systems (Hodbod and Eakin, 2015; Darnhofer et al., 2016). Agrifood systems encompass physical and social elements. The first category refers to natural resources and ecological factors, while the second includes all the social entities involved in agrifood production, processing, supply, and consumption. These entities interact and exchange practices which change over time, thus generating multiple scales and levels of interactions that are governed by institutions mediating between social and ecological components (Ericksen, 2008). The way interactivity patterns evolve, which depends on the multiple and often conflicting views, aims, and objectives of the participating actors, contributes to structural and institutional changes (Doherty et al., 2019). Hence, it is difficult to predict or even understand the emergent properties of agrifood systems, that is, how the whole (agrifood system) emerges from—and is more than the sum of—its parts (Leeuwis et al., 2021). Notably, these systems are open to external impacts originating from environmental, social, political, and economic changes (Ericksen, 2008), which are also hardly predictable. Hence, agrifood systems are in constant flux, changing structures, and continuously moving to new equilibria under the influence of social and ecological changes.

As Meuwissen et al. (2019) point out, agrifood systems perform multiple functions, having to cope with economic, social, institutional, and environmental challenges while maintaining the supply of both commodity and non-commodity outputs provided by farming activities (Van Huylenbroeck et al., 2007; Wilson, 2008). The capacity of such systems to be resilient depends on three interdependent (Spiegel et al., 2021) parameters: their robustness, which refers to their ability to react to external shocks by preserving their own pre-shock activities; their adaptability, that is a capability to modify the combination of available resources with no alteration of the current architecture of the system; their transformability, which involves a change in the combination of the resources, the structure and management of the system when external perturbations occur (Meuwissen et al., 2019; Buitenhuis et al., 2020).

Resilience and innovation are positively correlated. Resilient systems exhibit higher innovation potential because of their ability to generate innovative solutions to avoid stresses and shocks (Folke, 2006). In parallel, innovation increases the resilience *in* systems and *of* systems by promoting new forms of self-organization and fostering transformations as responses to crises and perturbations (Martin-Breen and Anderies, 2011). As the recently published report of the 5th SCAR notes, innovation has the goals to ensure nutritious, healthy, and sustainable food for all, facilitate the transition to circular agrifood systems, and promote diversity as an engine for resilience in our food, farm, and social systems (European Commission, 2020). Nevertheless, in policy documents, the emphasis is on the technological innovation. That is not surprising, given that the meaning of innovation is considered today as synonymous with commercialized technological innovation that aims to help the achievement of economic growth (von Schomberg and Blok, 2018).

Of course, technology has long been considered an accelerator of agrifood systems resilience. Already from the first steps of farm mechanization, scholars endorsed the idea that innovative technologies can improve farm production with positive impacts on the entire agrifood system. The Nobelist Lord Boyd-Orr (1950), in one of his essays, explained that "it is claimed that the land presently under cultivation could support twice the present world population if it were made to yield to the full capacity possible by modern technology" (p. 13). Adopting a similar stance, Raper (1946, p. 29) argued that, thanks to improved farming technologies, we can "create through moderate work enough goods and services for our needs, and have the time and energy and resources for our own personal growth." Today, intergovernmental and non-governmental organizations stress the importance of technological innovation for increasing economic, environmental, and social resilience (European Training Foundation European Bank, 2021; United Nations, 2021). Researchers also underline the potential of innovative technologies for building resilient agrifood systems (Weber et al., 2020; Khan et al., 2021; McClements et al., 2021). However, technological innovation is not a panacea able to solve any challenge that current agrifood systems confront.

Depending on their particular attributes, technologies have a different transformative potential, affecting in varying ways agrifood systems. In this study, we focus on three sets of technologies that present interest for innovation research and practice. The first one refers to the mega-technological trends (digital farming tools, nanotechnologies, and the like), which emerged as a promising solution to the problems that agrifood systems confront. The second concerns simpler, internetworking or platforming technologies that mediate other types of innovation. Beyond technological breakthroughs, such technologies also can and already do mediate the transformation of agrifood systems by promoting new organizational arrangements among actors and pursuing social goals. Hence, they give rise to a new breed of innovation (called poly-innovation in the present article) that focuses on creating positive social and organizational change. In addition, a third set includes small-scale—and sometimes commercially unattractive—technological micro-innovations, which can play a pivotal role in sustaining small-scale farming resilience.

In the present work, we pursue a three-fold aim. First, to theoretically analyze these three strategies and to present their main characteristics. Second, to explain their links with agrifood systems resilience. Third, to present the factors that reduce their potential to open up resilience-enhancing innovation trajectories for agrifood systems. To meet these purposes, we performed a narrative literature review, combining studies from diverge fields and linking knowledge on different topics (Baumeister and Leary, 1997; Pautasso, 2019). Instead of performing a systematic review, which would aim to answering specific research questions and use a criteria-based selection of articles, we leaned upon a narrative approach to provoke new lines of thinking and contribute to the discussion of the topics associated with the three examined innovation approaches[1].

The article is structured as follows. First, we offer a brief conceptualization of innovation, also presenting its different types. Then, we elaborate on the promising potential of responsible technological innovation for agrifood systems, and we expose some issues that require further consideration to responsibly approach the expected transformations. Thereupon, we present the possibilities and perils of poly-innovation. We continue by discussing technological micro-innovation, its potential contribution to building resilience among small-scale farmers, and some steps that need to be taken to promote it. Finally, we summarize the key points of our paper.

INNOVATION EXPLAINED

In one of the most influential works ever published in the field, Rogers (1983, p. 11) describes innovation as "an idea, practice, or object that is perceived as new by an individual or other unit of adoption." However, as Rogers explained, newness is a vague concept. Innovation is not necessarily equal to an invention since innovation often occurs without inventing anything (Brozen, 1951). As Zhuang et al. (1999) state, innovation may refer to a completely new invention, an improvement, or the implementation of an idea into a new application. For Van de Ven (1986), it is the perception of newness associated with an idea, formula, or approach that counts for defining it as innovative for some people, even if others see it as an imitation of something already existing. Plainly stated, an idea, process, or artifact can be perceived as new—and therefore innovative—by some actors and old, or not new, by some others.

The relevant literature, attributes two central characteristics to innovation. First, innovation is a dynamic process through which new ideas are created, implemented, and evaluated (Alves et al., 2007; Hansen and Birkinshaw, 2007; Mele and Russo-Spena, 2015). Scholars agree that innovation begins with an idea, which is developed and implemented to produce positive results (McAdam and McClelland, 2002; Taylor, 2017). Regardless of whether it emerges from the combination of old ideas or it is groundbreakingly new, innovation challenges the order of things in organizations, sectors, or industries (Van de Ven, 1986), having the potential to generate new forms of value (Ngugi et al., 2010; Russo-Spena and Mele, 2012; Reypens et al., 2016). Nevertheless, varying types of risks for both the innovators (Halman and Keizer, 1994; Fernandes and Paunov, 2015) and the society (Sebock and Pospisil, 2017; de Almeida et al., 2018) follow the innovation.

Second, innovation becomes. That is to say, it emerges through processes that take place and are validated within socio-material systems. Succinctly put, innovation evolves within systems consisting of social actors—and their socio-material practices—who experience the value that they co-produce by participating in the innovation process (Akaka et al., 2017; Chandler et al., 2019; Vargo et al., 2020). Notably, the actors who contribute to the development of innovation and the co-creation of value are not only firms and consumers. Policy bodies, educational institutes, and innovation support services are variously involved with these value co-production systems (Tödtling and Kaufmann, 1999). When the produced value is considered sufficient, innovation continues its path, attracting other actors, and evolving over time. When that is not the case, the innovation process fails (Lioutas et al., 2022).

[1]To identify articles relevant to the purpose of our study, we searched Scopus and Google Scholar databases. The terms initially used for the present review were: "responsible innovation" AND "technology" for the part of review referring to responsible technological innovation (key source: Owen et al., 2013); "technological innovation" AND "organizational innovation" OR "social innovation" to find articles referring to poly-innovation (key source: Dubé et al., 2014); "technology" AND "small-scale innovations" (key source: Molina-Maturano et al., 2020), complemented by the terms "resilience" AND "agriculture" OR "agrifood" in a next step. Nevertheless, since our aim was not to perform a systematic review but to sketch a theoretical framework and present some new ideas, the search expanded to other fields.

Innovation can be distinguished into technological and non-technological, depending on what the main attribute of the innovative idea is. Technological innovation, which represents a major trend in the literature of agrifood systems resilience (Agnusdei and Coluccia, 2022), at first glance, seems the most easily defined type. Nevertheless, there is considerable confusion around the term and, therefore, finding a commonly accepted definition is not an easy task. The term can either refer to the new combination of productive factors, following the Schumpeterian tradition (Schumpeter, 1939), or—as in any other innovation type—to the adoption of technologies by innovators (Crossan and Apaydin, 2010), which represents the broader use of the phrase in the agricultural innovation literature. Nevertheless, technological innovation does not refer exclusively to the physical dimension of technological artifacts. Technology encompasses a range of phenomena, both hardware (e.g., devices) and software (processes, methods) (Vargo et al., 2015), which, when combined in novel ways represent potential technological innovations.

Non-technological innovation, on the other hand, refers to those innovative solutions or practices that do not involve technologies. New marketing strategies, organizational forms, and business models construct this category (Mothe and Nguyen-Thi, 2012; Geldes et al., 2017; Geissdoerfer et al., 2018). Actors usually develop (instead of adopting) a non-technological innovation by changing marketing methods, altering elements of their products and/or services, or remodeling organizational methods, business practices, and relationships with other entities (Schmidt and Rammer, 2007). In the agrifood sector, non-technological innovation is a strategy used by many actors (Fuentes and Soto, 2015), thus recently attracting the interest of researchers (e.g., Klerkx et al., 2010; Lambrecht et al., 2014; Sebok et al., 2020; Vecchio et al., 2020).

Looking at the ambitions concerning the expected outcomes of the process, one can identify two camps of innovations. The first one is business (or commercial) innovation; a type emphasizing the attempts to satisfy some market needs by innovating (with or without involving technological innovation), receiving in return a profit. Sawhney et al. (2006, p. 76) define business innovation as "the creation of substantial new value for customers and the firm by creatively changing one or more dimensions of the business system." In this view, business innovation is market-oriented, and aims to increase the wealth of the actor(s) initiating or adopting it and the value that customers experience.

At the other end of the spectrum, social innovation emerged as a response to the quest for increasing social performance (Castro-Spila et al., 2016). It also aims at meeting particular needs that are not provided by existing markets. One of its main identifying features is the involvement of users in the production process (OECD, 2011). Although the term is often used to denote a non-profit oriented activity, Pol and Ville (2009) explain that apart from those (pure) social innovations that are initiated and implemented without a profit motive, many other attempts to improve "either the quality or the quantity of life" (p. 881)—which is the core attribute of social innovation—involve profit-making.

THE TURN TO RESPONSIBLE TECHNOLOGICAL INNOVATION

A Brief Conceptualization

The recent emphasis on sustainable transformations of agrifood systems through technological escalation, along with the emergence of highly innovative and often radical technologies, have led researchers and policy-makers to introduce into their agendas the issue of responsibility in the technological innovation process. While digital tools like sensors, Internet of Things platforms, autonomous robots and vehicles, big data, drones, and other technology-mediated developments such as genome editing, 3D food printing, or food biofortification technologies seem enlightening and able to boost sustainable intensification of production with a high potential for agrifood systems resilience, some new dimensions like the societal values, needs, and implications of technology for the society have to be taken into account (Eastwood et al., 2019).

A critical point of concern is the inability to predict the future impacts of high-tech innovation on agrifood systems. The gap between expectations and reality can be broad, whereas, at times, counterintuitive or adverse effects in the long term are possible. Hodbod and Eakin (2015) give an example of how the introduction of improved Bt cotton varieties increased the productivity of US cotton farming with some positive impacts for systems resilience, generating however ecological risks and new power structures within the system, therefore jeopardizing its long-term resilience. Other evidence suggests that, despite their contribution to productivity increase, innovative technologies can lead to environmental degradation through intensification and the consequent loss of biodiversity and water pollution (Allouche, 2011) or by producing side-effects to the quality of natural resources (Berkes et al., 2006). At the farm level, as Ashkenazy et al. (2018) explain, technological modernization can positively affect farmers' short-term economic results without ensuring the long-time resilience of their enterprises. Technological innovation requires investments that create hard-to-service debts, especially for small-scale farmers (Knickel et al., 2018). In addition, innovative technologies are possibly accompanied by several socio-ethical issues, such as technological dependence (Borisov and Danilova, 2020), the centralization of power in technology providers and major supply chain players (Freidberg, 2020; Prause et al., 2021), the creation of inequalities and divides within agrifood systems (Lioutas et al., 2021), and the disturbances in prevailing ethics (Carbonell, 2016) and established conditions of producing, collaborating or competing (Lioutas and Charatsari, in press). The observation that, even if the positive impacts of technological innovations surpass their potential negative outcomes, the transition to a new status quo for agrifood systems can be acute or even painful for some of the involved actors is not new (Kifer et al., 1940). Given that new technologies are associated with a high level of uncertainty about their transformative potential (Arthur, 2009), they encompass a threatening nature (Jonas, 1982) that requires responsible approaches to their promotion.

The realization that technological innovation comes along with some societal risks led to the emergence of a new wave of thinking, emphasizing the role of responsibility in the innovation process. Following earlier attempts to underline the ethical principles and provide guidelines for innovating within and for the society (Chadwick and Zwart, 2013), Responsible Innovation (Owen et al., 2013) or Responsible Research and Innovation (Stilgoe et al., 2013) opened up a new and vivid scientific debate with the purpose of countervailing economic with socio-cultural and environmental aspects in innovation processes (Gremmen et al., 2019).

Responsible Research and Innovation (RRI) focuses on both the positive potential of new technologies by trying to answer what do they allow actors to do, and their normative dimension, by inquiring what should technological innovation do and for whom. As von Schomberg (2011, p. 9) posits, RRI "is a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products (in order to allow a proper embedding of scientific and technological advances in our society)."

Central to RRI philosophy is the emphasis on the need to take responsibility for the consequences of a determined innovation path through a strong consideration of the multiple values behind the development and implementation of new technologies (Bronson, 2019). Adopting such an approach requires an in-depth analysis of the ARIR sequence: anticipation, reflexivity, inclusion, responsiveness (Stilgoe et al., 2013). Anticipation is set in the context of the "What if?" question, focusing on the potential environmental and socio-ethical risks related to innovation. As Stilgoe et al. (2013, p. 1570) point out, anticipation "involves systematic thinking aimed at increasing resilience, while revealing new opportunities for innovation and the shaping of agendas for socially-robust risk research."

Reflexivity is the capability to increase/minimize the positive/negative impacts and specify at what cost for the society or specific social groups innovation can pay off by considering in a broad sense all the actors involved in the innovation process. Reflexivity is drawn on Giddens (1984) theory of self-monitoring behavior adopted by some social actors under the hypothesis that other actors do the same. As Bolz and de Bruin (2019) explain, reflexivity concerns both the outcomes of the innovation process and the process itself. When actors reflect on the practices that they are using during the technological innovation process, or, as Stilgoe et al. (2013) put it, they hold a mirror up to their own activities, commitments, and assumptions, they can understand how their actions affect other actors and the orbit of innovation. Although the concept of reflexivity is not new in agrifood systems research—see, for instance, Ray (1999) work on reflexive modernization of agrifood systems—in the RRI vocabulary took a specific sense: the procedure through which actors attempt to minimize the negative impacts of technological innovation increasing in parallel its positive potential.

To achieve higher levels of reflexive monitoring of the innovation process, RRI considers the inclusion of different stakeholders in the innovation decision-making processes as a sine-qua-non condition (Jakobsen et al., 2019). The amalgamation of varying interests and the representation of the voices of lay people in the governance of the innovation process (Stilgoe et al., 2013) is expected to help anticipate a broad range of potential impacts by considering public concerns when developing technologies (Asveld et al., 2019; Fraser, in press). Of course, inclusiveness is a context-specific concept. For instance, between different innovation approaches, there might be significant differences. Wakunuma et al. (2021) distinguish between capital-oriented and livelihood-oriented approaches. The first category refers to innovations generated through private and public investments and supports the involvement of academia, policy-makers, and the industry. The second concerns the addressing of local and rural-oriented challenges through tailor-made adaptations of the RRI agenda and involves actors such as communities and cooperatives.

Finally, responsiveness refers to the ability to promote change in the innovation trajectory as an answer to emerging needs and societal instances. As Di Giulio et al. (2016, p. 92) explain, it "implies acknowledging and responding effectively and transparently to the perspectives of all those with a stake in the outcomes of innovation." Responsiveness, therefore, represents the action element of RRI: one that translates social input and emerging knowledge into action aimed at correcting innovation trajectories when needed (Sonck et al., 2017).

The idea of responsible innovation has a central position in European innovation policy, promoting the engagement of citizen organizations, civil society, and end-users in the co-development of innovations and co-construction of innovation paths as a way to increase the levels of trust between science and society (European Commission, 2019). Akin or complementary approaches, like safe-by-design (van Gelder et al., 2021), co-design of technologies (Eastwood et al., 2022) and human-centered design (McCampbell et al., in press), ethical design (Leone, 2017), responsible innovation ecosystems (Ntsondé and Aggeri, 2017; Stahl, 2022), or the ethics-of-ethics (Özdemir, 2019) also promise to facilitate the discussion of how innovative technologies can increase agrifood systems resilience and societal wellbeing without leading to potential negative environmental and social impacts. The philosophical premises of RRI gain increasing popularity beyond the boundaries of the European Union, being a matter of discussion (Chaturvedi et al., 2016; Prasad, 2020) or already used in the practice of agrifood-related technological innovation implementation (Eastwood et al., 2019; Espig et al., in press; McCampbell et al., in press).

Promises, Challenges and Open Issues

The links between RRI and agrifood systems resilience are easy to prove. Focusing on the potential impacts of innovative technologies on society and the environment, RRI moves beyond simple economic evaluations by incorporating grand challenges into the innovation agenda (Von Schomberg, 2014) and stressing the need to understand the multiple equilibria that innovative technologies can create in the future. Research done so far offers some intriguing insights into how some mega-technological trends like nano-agrifoods or digital agricultural technologies can transform agrifood systems, providing policy-makers and innovation designers with crucial insights. For instance, Grieger et al. (2021), using a mixed research design, revealed the existence of concerns about the potential environmental and public health impacts of nanotechnologies, also uncovering some doubts about the necessity of developing some of these technological advancements. Simelton and McCampbell (2021), building upon the RRI template, offer technical and organizational recommendations on how to design digital applications aimed at helping farmers increase their production efficiency and, consequently, the economic resilience of their farms.

Moreover, by acknowledging the emerging nature of innovation, the RRI framework can be used as a compass, directing innovation paths toward desirable directions or, at least, correcting innovation trajectories when environmental or social issues are at stake. Although scholarly research to date has put limited emphasis on the dimension of responsiveness (Burget et al., 2017), considering the need to undertake risk management action when technological innovations have unwanted consequences is a step toward protecting the resilience of agrifood systems. By offering policy guidelines and stressing the potential positive and negative impacts of technological innovations, RRI exercises can facilitate the development of technologies during the innovation process, leading to resilience-enhancing modifications. In sum, RRI provides a very functional template for monitoring the technological innovation process and intervening when innovation paths need corrective interventions.

However, despite its promising potential for the future of technological innovation in the agrifood sector, RRI presents some limitations that need to be taken into account when designing and applying technological innovation in praxis. The first point of criticism toward RRI is its focus on the academic use of the framework. While technological innovation is often—if not most of the time—market-driven, the concept of RRI and its main attributes remain somewhat enclosed in the academic/research boundaries. However, commercialized technological innovation is often guided by different principles than those that might govern academic research (Lubberink et al., 2017). Notably, after more than 10 years of existence, RRI has not yet managed to effectively promote its ideas across the industry. Indeed, Chatfield et al. (2017) found that only a limited proportion of their interviewees (seven out of 30 holders or key-employees in ICT companies located in eleven European countries) were aware of the RRI. Mehari et al. (2022) also discovered that companies that operate in the Finish energy sector were not aware of the RRI concept. Although both studies did not focus on agrifood-related innovation, they can offer an impression of the extent to which RRI thinking has penetrated industrial settings.

Beyond that, one of the most pivotal issues when engaging RRI in the agrifood innovation process concerns the practical application difficulties (Espig et al., in press). To innovate responsibly seems easier said than done. The multiple scales and levels of interactions among actors and the constant flux characterizing the interactivities between social entities and the physical dimension of agrifood systems complicate the praxis of innovation. Sometimes the expectations from implementing responsible innovation approaches can be very high, and the motivations of different innovators (or even actors not involved but affected by the innovation process, such as competitors or other industry players) are unknown (Kuzma and Roberts, 2018). Indeed, actors often attempt to lead innovation to specific paths by leveraging essential resources (technology, relational assets, knowledge) to prioritize their agendas (Lioutas and Charatsari, in press). Information asymmetries, often pursued within market environments because they can give actors competitive advantages, thus helping them survive and succeed, may also hinder the scope and effectiveness of RRI (Bhaduri and Talat, 2020). Transparency, which is a requirement for reflecting upon the process and responding to emerging needs, reduces these asymmetries and, hence, is not always an easy choice to make for private actors (von Schomberg and Blok, 2018).

Public participation in innovation governance is also an issue open to debate. On the one hand, the recent emphasis on public acceptance of technologies through engaging actors in the process (Delgado and Åm, 2018), goes against the very nature of RRI as it is highlighted in its fundamental premises (Stilgoe et al., 2013; von Schomberg, 2013). A potential shift from engaging citizens in the co-shaping of technology design to involving them as a means to promote acceptance of technological innovation can change the core principle of innovating "with and *for*" society (Owen et al., 2012). On the other hand, the central question of "who is to be included in the process?" remains open to different answers (Rivard and Lehoux, 2020). When inviting actors who are not actively involved in the innovation process, the dialogue on innovation trajectories can take the form of a structural procedure, conforming to issue framings and following pre-designed paths—see Bauer et al. (2021) for detailed elaboration. Hence, the risk of reinforcing consensus and promoting uniform views increases (Sykes and Macnaghten, 2013). Notably, as research has shown, engaging only innovators can also be problematic. Actors who directly or indirectly participate in the innovation process often adopt a myopic stance by concentrating on a single and relevant to their activities and networks subsector of economic and/or social activity, whereas indeterminacy and ignorance (i.e., the unknown unknowns and the inability to predict the future consequences of their actions) reduce the capacity to foresight how technologies will affect other sectors (Charatsari et al., in press). Blok and Lemmens (2015) offer an example of how indeterminacy may play in a technology-intensive field: biofuel production. Biofuel's emergence as a response to the energy shortages was associated with optimistic anticipations, generating great expectations to stakeholders. However, some unanticipated indirect impacts emerged after some years because a part of the cultivated crops was directed toward the production of biofuel, thus reducing the quantities of available foodstuffs and eventually increasing food prices.

Another risk refers to the exclusion of groups that receive some of the indirect or linkage impacts of innovation. Such effects are not always easily identifiable, posing practical difficulties to the inclusion of possibly affected groups. In RRI thinking, public organizations and civic society can adequately represent the interests of most social groups, and that holds much truth. However, achieving consilience is a challenging task. Particularly when the interest and value priorities of the actors speaking on behalf of the public and those of private innovation initiators are conflicting, the outcomes of the reflection process are rarely constructive (Callegari and Mikhailova, 2021). An additional issue that should be considered is engagement fatigue, which refers to the unwillingness or the inability of the more neutral actors to partake in the process (Rip, 2014).

Moreover, even though in publicly-funded innovation projects it is relatively easy to develop initiatives that ensure public representation and inclusion of key stakeholders in the anticipation process, a vital question is how public participation can be promoted in market-driven technological innovation (Arnaldi et al., 2015). Equally important, albeit less discussed in the RRI literature, is the issue of power imbalance among the actors who participate in the innovation (and reflection) process. Since funders and technology producers are expected to have a louder voice, they can have a more potent influence on the innovation path than other actors (von Schomberg and Blok, 2018).

Shifting our focus on the reflection process, a new question comes to the fore: when should the process begin? A novel technology emerges as an unproven solution to problems that exist today and perhaps, are expected to increase in the future. Nevertheless, before its final release, there are only limited opportunities for most social entities to anticipate and reflect upon its impacts. Positivity biases are always possible because the expected functionality of technologies is often overestimated, thus obscuring potential alternatives and reducing imagination of different choices (Collingridge, 1992). On the other hand, after introducing a new technology into the market, it is easier for stakeholders to perform an evidence-informed evaluation; nevertheless, the opportunities to rectify the trajectories of technology are limited (Sollie, 2007; Lioutas et al., 2021).

However, despite the above-mentioned limitations, RRI can help overcome some of the negative impacts of technological innovation on agrifood systems resilience. By emphasizing the co-shaping of technological transformations and attempting to foresee the futures that innovative technologies can create, RRI integrates resilience-related issues into technology development (Stilgoe et al., 2013). Since RRI is a concept—and approach—still under construction (Owen et al., 2021), it has a great potential to promote resilience-enhancing sociotechnical transformations of agrifood systems.

POLY-INNOVATION AS AN EMERGING PRACTICE

A Brief Conceptualization

RRI frameworks, aiming at designing socially desirable technologies, tend to attribute high emphasis on commercialized technological innovations. Consequently, the focus is on the "technofication" of innovation, neglecting other potential routes of innovating (von Schomberg and Blok, 2018). Hence, RRI has not yet fully included social innovation into its agenda, despite the recent prominence given by policies (especially in the European Union) to it (Khan et al., 2016). Moreover, despite the clear links between technological and organizational innovation—owing to the fact that some of the technologies that RRI researchers focus on promote or require organizational changes (Merz, 2009; Antonova, 2015), and to the mediating role that some technologies play in organizational innovations (Edwards-Schachter, 2018)—the organizational nature of innovation is also underrepresented in the relevant discussion.

Not surprisingly, companies have already attempted to link business and technological with organizational and social innovation through varying approaches and business models. For instance, *Hello tractor* (https://hellotractor.com/), a Nigerian start-up, developed a farm equipment-sharing digital platform connecting tractor owners and small-scale farmers who lack the necessary equipment to cultivate their fields. Through a simple online application, farmers who need machinery are connected with equipment owners, having the potential to book a tractor and schedule their tractor service in advance. The innovative business model used by hello tractor is based on technological innovations, referring to the application and the platform, the global positioning systems used, and even the tractors that—for some of the smallholders using the platform—represent innovations. Nevertheless, it also encompasses non-technological innovations, since it is based on and promotes a different form of organization, connecting owners and seekers and building relationships with other actors (given that in some cases booking agents enter farmers' geospatial information in the platform). Finally, by improving the working conditions of small-scale farmers, offering an extra income to tractor owners and booking agents, and potentially improving the production and quality of seekers' crops, it encloses elements of social innovation (see also Zhou, 2016; Okunlola and Adenmosun, 2017; Kolk and Ciulli, 2020; Daum et al., 2021).

Publicly-funded projects, especially in the European Union, began to embrace such approaches. By espousing the logic of the sharing economy, consortia formed by public and private actors develop solutions that aim at the reorganization of the agrifood system and the delivery of positive social impacts through technologies that connect different actors. For instance, within the framework of the EU GIVE project (https://www.eugiveproject.eu/), an application called Foodity for connecting high-end hotels and restaurants with customers interested in buying food surplus at low prices has been developed. Uber-like platforming technologies are often used in such projects to promote innovative forms of organization within agrifood systems and facilitate the generation of benefits for both the participating companies and the society (through reducing food waste and improving low-income consumers' access to food).

Contrary to Hello tractor, where technological innovation lies at the heart of its business model, Foodity is a technological innovation—based on what Lee et al. (2018) term "internetworking technology"—used as a means to facilitate social innovation. However, in both cases, which are just some of the many relevant initiatives that have been recently undertaken, technological and non-technological innovations are combined, whereas business and social innovation co-exist, enabling the achievement of both societal and entrepreneurial goals. The central idea behind both examples is the promotion of bundles of innovative solutions that create a competitive advantage for companies (business innovation) while they also have a social value (social innovation) and incorporate technological and non-technological innovations at different levels into their modus operandi. Hence, such a perspective of innovation enhances the transformability and, consequently, the resilience potential of agrifood systems.

The term poly-innovation used in this article refers to a combination of the previously mentioned types of innovation. It describes the implementation of innovative ideas that use novel technology to promote innovative organizational and/or marketing elements, aiming at enhancing both the value that a firm receives and the social value. Dubé et al. (2014) were among the first to advocate the need for a new paradigm in innovation, which will combine elements of technological, social, and organizational innovation mainly focused on the wellbeing of underserved from mainstream innovation approaches segments or social groups. In their view, technologies can be bundled with social and organizational innovations to create "convergent outcomes for precisely targeted, achievable, and time-bound challenges" (Dubé et al., 2014, p. 121). Without relying on central planning and control strategies, this approach—"convergent innovation" in Dubé et al. (2012) words—is based on the involvement of different sectors in the innovation process, facilitating the attainment of economic, and social goals.

Promises, Challenges and Open Issues

As a socially-intensive practice, poly-innovation shifts the emphasis from the role of technologies as game-changers to that of technologies as mediators of resilience-enhancing social behavior. Low-cost technologies, in this sense, are used as a means to facilitate both organizational (the re-organization of the food production or distribution practice) and social innovation aimed at the achievement of high-end targets (Davies et al., 2017), like the increase of small-scale farmers' income, hunger elimination and food waste reduction. By increasing the revenues of market actors (Michelini et al., 2018), opening up micro-entrepreneurial opportunities (Davies and Garrett, 2018), reducing consumers' food expenses (Falcone and Imbert, 2017), or improving farmers' wellbeing (Chona, 2021), the innovative organizational arrangements that poly-innovation creates contribute to the economic and social sustainability of agrifood systems. In parallel, indications confirm that poly-innovation strategies reduce the greenhouse gas footprint of food distribution (Makov et al., 2020), thus increasing the environmental performance of agrifood systems. The formation of sub-systems that are characterized by increasing adaptability to external shocks and stresses, and the emergence of some new resources like solidarity and community action (Michelini et al., 2018) that improve the systemic adaptive capacity and shape desirable changes (Folke, 2006), are probably the two most important contributions of poly-innovation to agrifood systems resilience.

However, it is questionable whether such approaches reduce or avoid recreating the inequalities observed in the agrifood systems (Simonovits and Balázs, 2022). For example, Hello tractor's positive social impacts cannot easily extend beyond the limits of specific communities, possibly leading to asymmetrical competition between geographic regions. In other cases, the reliance on technologies excludes those individuals who lack access or capacity to use them from the innovation process. Moreover, the uberization of some sub-units of agrifood systems and the wide use of Foodity-like approaches may affect the economic viability of niche food distribution schemes, like short food supply chains or community-supported forms of agriculture, which also target alternative consumer segments. Finally, the pursuit of social and organizational innovation is often accompanied by possible negative impacts, such as the justification of inactivity on the part of the state, conflicts emerging from the new power relations (Ravazzoli and Valero, 2020), and the disempowerment of some actors (Ravazzoli et al., 2021). The lack of a central coordination mechanism, albeit allowing spaces for creativity and transformation, increases the uncertainty for the future trajectories of poly-innovation approaches.

MICRO-INNOVATION: A NEGLECTED SPECIES

A Brief Conceptualization

The dominant line of thinking in technological innovation research, influenced by the philosophy of diffusing innovations, emphasizes the creation of innovative solutions that apply to problems faced by numerous actors. The central hypothesis here is that social groups (or sectors) consist of actors who share similar attributes, have common concerns, and face akin problems; for instance, the farmers living in a specific area and cultivating the same crop. Although there is nothing wrong with generating technologies that aim to solve the problems of the many (e.g., of whole sectors or social groups), the unique nature of each organization generates the need for tailor-made solutions that can help overcome particular problems.

At the farm level, most technological innovations intend to solve the problems or address the needs of a practically non-existing being: the average farmer. Technologies designed in the past, such as tractors, pesticides, or irrigation systems, had as their main aim to facilitate farmers increase their production efficiency and, indeed, achieved such progress. However, different regions are characterized by varying innovation potentials, whereas they face divergent problems and confront dissimilar barriers (Tödtling and Trippl, 2005). Even when concentrating on a specific region, farms are characterized by considerable differences in soil properties, fertility, microclimatic conditions, water availability, or quality, whereas their structural features are also different. Hence, albeit useful for many farmers, technology may not produce the expected results for others. In addition, technologies may not be suited to the "local way of doing things" (Ashkenazy et al., 2018), to the existing technological infrastructure, or the symbolic representations of particular farming types (Lioutas and Charatsari, 2020).

To cope with the lack of good fit between their needs and the technologies available, farmers traditionally adapted technological innovations to the conditions under which they operate. For instance, McPhee and Aird (2013) explain potential adaptations Australian farmers made to grain harvesters to match the working characteristics of other equipment. Kumar et al. (2015) briefly present a modified version of drum seeder produced by Indian farmers. Beyond modification, evidence suggests that, in some cases, farmers create their own machinery to better serve their needs or find cheap ways to improve the effectiveness of their enterprises. Leitgeb et al. (2014, p. 52), investigating the outcomes of Cuban farmers' experimentation processes, discuss the development of new equipment such as "a multi-plow with 28 different uses, an irrigation programming system that runs without electricity or fossil energy, or a sowing tool built from recycled material." Bicycle irrigation pumps, small-displacement motorcycles used for plowing, harrowing, and sowing purposes, and many other technical applications have been developed in different regions to serve different needs at low cost (see Molina-Maturano et al., 2020 for a list of relevant innovations).

That type of "micro-innovation" emerges as an attempt to solve problems and inefficiencies and is essentially autonomous, in the sense that actors autonomously develop innovative solutions through iterative trial and error procedures (Bahadur and Doczi, 2016). Micro-innovating involves what Tremblay (1998) terms informal changes: incremental improvements, initiated by user organizations rather than solutions developed by others and then adopted through formal diffusion processes. As Rosenberg and Nathan (1982) note, that type of innovation emerges as a by-product of the production activities. While operating, actors and/or organizations observe the effectiveness of the process and understand the need for specific improvements that can be realized either by adapting existing technological solutions or by creating new ones. Notably, people modify technologies even when they are satisfied with their performance to achieve a better fit to their (changing over time) needs (Morrison et al., 2000). Or, individually or collectively, they develop their own technologies (Pineda, 2018). In resource-rich contexts, individuals or organizations apply their competencies (human creativity, technology, finances, infrastructures, networks) to create innovative solutions for themselves. However, in resource-constrained environments, bricolage strategies are used to re-assemble technologies or to generate new ones that aim at helping to solve problems or exploit opportunities (Baker and Nelson, 2005). Experimentation, tinkering, and generation of solutions from the resources at hand represent the main routes through which such strategy is executed (Gurca, 2016).

Promises, Challenges, and Open Issues

Without being always a matter of admiration like their counterpart market-driven technologies, and often being created under the principle that "necessity is the mother of inversion," micro-innovations can offer advantages to innovators, having in parallel substantial community impacts (Shepherd et al., 2020). Micro-innovations can spread within social systems either through imitation or following a more formalized production strategy, through a process known as frugal (Sissoko and Castiaux, 2018), jugaad (Radjou et al., 2012), grassroots (Gupta, 2020), or bottom of the pyramid innovation (Prahalad, 2012). Although scaling out is not a central concern for many micro-innovators and patenting is not a standard strategy like in industrial settings, many examples confirm that the commercial use of micro-innovations by farmers is possible. Pansera and Sarkar (2016) present the case of an Indian farmer who developed a mobile cotton stripper machine, which granted a patent in the USA, also helping local farmers improve their working and living conditions.

Being available at affordable prices, commercialized micro-innovations can offer tailor-made solutions to small-scale farmers who cannot afford the cost of standard technologies, thus contributing to the resilience of their enterprises. Arguably, even though those farmers form a large segment of the farming population in low- and lower-middle-income countries, considerably contributing to the total value of global food production (Lowder et al., 2021), they are an unattractive cluster for mainstream technology providers (Rangaswamy and Densmore, 2013). Hence, the commercialization of micro-innovations via open design can offset the lack of technological resources, representing a survival strategy for them.

To support the generation and promotion of micro-innovation, there is a need for both finance and scaling that development organizations should embrace (Bahadur and Doczi, 2016). Donors, non-governmental organizations, and local manufacturers can co-shape the development and diffusion process (Sissoko and Castiaux, 2018) by offering technical and institutional support to micro-innovators. However, helping donors understand the importance of micro-innovation can be a difficult task because of the low public appreciation such innovations enjoy in the Global North. The development of open-source networks—like the case of Open Source Ecology (Thomson and Jakubowski, 2012)—can further spread micro-innovations, also helping their continuous improvement and optimization.

CONCLUDING REMARKS

In the present article, we discussed three different lines of technological innovation in agrifood systems and their links with resilience. Although our study is not a systematic review—which can be considered as a limitation by some advocates of reviews that focus on quantitative taxonomies and use strictly selected inclusion criteria—it summarizes the knowledge available to date on responsible technological innovation, poly-innovation, and micro-innovation, and the relation of these innovation paths to agrifood systems resilience (**Table 1**).

Responsible technological innovation emerged as a response to the growing concerns associated with the impacts of technological breakthroughs like digital agricultural technologies or nanotechnology applications on agrifood systems. RRI is a functional framework for anticipating positive and unintended negative societal impacts through the inclusion of different interests in innovation governance, the reflection upon the outcomes of innovation and the process itself, and the undertaking of responsive actions when needed. RRI, we argue, despite the many practical application difficulties associated with

TABLE 1 | Sets of technologies, associated innovation paths, links with agrifood systems resilience, and open issues.

Technologies	Innovation path	Desirable impacts on the resilience of agrifood systems	Open issues
Mega-technological trends (e.g., digital farming technologies, nanotechnologies)	Responsible technological innovation	- Uncovering of risks or threats - Rectification of innovation trajectories when needed - Collaborative governance of innovation	Difficulties in: - Applying the principles of responsible innovation in praxis, - Selecting who should be included in or excluded from the process of responsible innovation governance, - Anticipating the impacts of technologies without bias
Internetworking technologies, connecting actors and facilitating transactions	Poly-innovation	- Emphasis on resilience - Promotion of resilience-enhancing social behavior - Creation of resilient sub-systems within the broader agrifood system	- Potential reproduction of inequalities - Disruptions to niches operating within agrifood systems
Small-scale Jugaad technologies often produced through bricolage	Micro-innovation	- Development of technologies tailored to the particular contexts and needs of resource-poor actors - Low-cost-low-risk approach, enhancing small-scale farmers' resilience	- Limited (if any) finance of relevant initiatives - Lack of technical and institutional support

the unclear rules behind the formation of innovation governance frames, the overconfidence in the capacity of the actors involved to effectively anticipate potential impacts, and the somewhat overemphasized concept of public acceptance, it remains a well-conceptualized approach that has to offer crucial insights into how technological innovation can enhance the resilience of agrifood systems.

Poly-innovation approaches, shifting the focus on the social and organizational dimensions of innovating, have gained increased popularity in recent years. In this line of thinking, internetworking technologies are used as mediators of positive changes in the agrifood system. Following the principles of sharing economy, poly-innovation attains the achievement of goals such as food waste reduction or the increase of small-scale farmers' economic wellbeing. The bundling of technologies with social goals and organizational re-arrangements between different actors can positively affect the resilience of agrifood systems. Nevertheless, concerns about the feasibility of the food uberization which such approaches promote generate the need for crafting relevant policies that will pose rules on how poly-innovation should unfold.

Although responsible innovation and poly-innovation represent major trends, micro-innovation is a survival strategy for small-scale farmers, especially in low-income countries. Micro-innovation can improve farmers' livelihoods, sustaining their existence within agrifood systems. However, having limited—if any—support from the private sector and public research, it is impossible to reach its full potential. Promoting this type of innovation is a challenging task since the target market of micro-innovations is commercially unattractive, and policies have not yet found effective ways to scan for and diffuse relevant technologies.

By presenting these three different strategies and approaches to technological innovation, this essay contributes to the ongoing discussion of the role of technological innovation in enhancing agrifood systems resilience. Responsible innovation approaches, poly-innovation initiatives, and micro-innovations can initiate positive transformations in current agrifood systems, yet at different levels and at varying degrees. The potential of all three approaches is high. Nevertheless, open issues requiring the attention of policy remain to be addressed. Academics and policy-makers have much to learn and do to effectively resolve them.

AUTHOR CONTRIBUTIONS

CC: conceptualization, methodology, and writing—review and editing. EL, MD, and YV: conceptualization and writing—review and editing. All authors contributed to the article and approved the submitted version.

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