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Research article

A three-pronged approach to the digitalization–innovation–sustainable rural development nexus among Italian farms

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Abstract: Recent studies have pointed out how digital innovations may boost more sustainable farming systems and have positive impacts on supporting the trajectories of smart rural development. The present work aims to analyze possible connections among digitalization, innovation and sustainable rural development through a three-pronged nexus thinking approach. This link is examined from a "discrete context" perspective, by assuming heterogeneity (which means that differences among farms may emerge in the process of adopting innovation) as a characteristic in adopting innovation and by investigating the potential impacts on local rural development. The empirical analysis draws on secondary sources, taking farms from the last Italian census of agriculture into account. Through a multivariate analysis, farms are grouped into homogenous clusters according to different types of nexuses. The results reveal a very interesting reality characterized by high levels of territorial heterogeneity in the adoption of digital and innovative solutions, bringing about scattered geographies of nexuses in the Italian farming system.

Keywords: digitalization–innovation–sustainability nexus; Italian agriculture; smart rural development

1. Introduction

Digitainability, combining actions oriented toward either digitalization and sustainability [1], has gained ground in the policy agenda and in addressing the issue of sustainable agrifood systems. Digitalization is a fundamental driver of innovation that, at the same time, may boost sustainable agrifood systems and smart rural development [2]. In fact, digital solutions foster higher levels of sustainability in the farming sector, thereby contributing to the development of more sustainable, resilient, and multifunctional farming systems [3]. Moreover, digitalization is considered to be an enabling technology for sustainable agriculture [4], and a key driver to enhance rural development processes [5]. As a matter of fact, the adoption of digital tools is often accompanied by investment strategies aimed at strengthening farms' sustainability, thus creating a virtuous circle based on the digitalization–innovation–sustainability nexus.

On the other side, the disruptive role of digital solutions [6] raises concerns about two main issues that must be considered [7,8], namely

- Directionality, concerning which smart solution fits best within certain business contexts;
- Non-neutrality, i.e., the risk of excluding potential beneficiaries from the advantages of new digital technologies.

As a consequence, potential effects of "misconfigured innovations" emerge [9], which call for broader analytical perspectives based on the idea that "the digitalisation of agriculture is a political and ecological process representing a further ingredient of the uneven and combined patterns of the capitalist development of agriculture" [10].

This risk may be linked to context-related variables, and, consequently, have diversified impacts on agrifood systems and local development. As a matter of fact, scholars have pointed out that non-neutrality is particularly associated with small-scale farmers, especially those who are elderly, less educated, and located in remote and/or marginalized areas [7]. Therefore, assuming digitalization as a social process implies acknowledging different potential impacts at the individual and local level. Moreover, the impact of digitalization cannot be separated from the impact on the dynamics of sustainable transition, as pointed out in the twin transition approaches, combining ecological and digital transition [11]. These approaches analyze the twin transition in the framework of transformative innovation, addressing "the systemic causes of societal problems and activates systemic mechanisms to fix them" [12]. The complexity of the processes may bring about high levels of heterogeneity, as "heterogeneity among farmers is the main cause of different levels of adoption" [13].

This paper is set against this background with the purpose of exploring the nexuses of digitalization, innovation, and sustainable rural development. More precisely, the research question we aim to answer through our analysis is as follows.

RQ1: What are the linkages among the adoption of digital solutions, innovation, and strategies of rural development implemented at farm level?

To answer the research question, our paper assumes a nexus thinking perspective [14].

Widely used for exploring the water–energy nexus to analyze potential solutions for a more efficient use of natural resources and to boost sustainable adaptation [15], the nexus approach has also been used for other purposes. In our paper, through a micro-level perspective focused on the farms, we focus on a three-pronged approach that considers three dimensions [14] by exploring the links among digitalization, innovation, and sustainable rural development. To the best of our knowledge, these nexuses have not been explored in the literature, despite them deserving attention. Therefore, our

paper fills a gap by providing an original contribution to the existing body of work.

Accordingly, the analysis tries to explore:

a. The adoption of digital solutions and/or innovation at the farm level;
b. The links between innovative strategies and actions targeted towards boosting sustainable farming systems and territorial strategies of rural development.

As shown in Figure 1, the nexus thinking perspective aims to test the contemporary presence of either the introduction of digital solutions, the adoption of innovation, or strategies of sustainable rural development through farm boundary shifts, which depicts a three-pronged nexus. Alternatively, only two nexuses or no nexus may emerge.

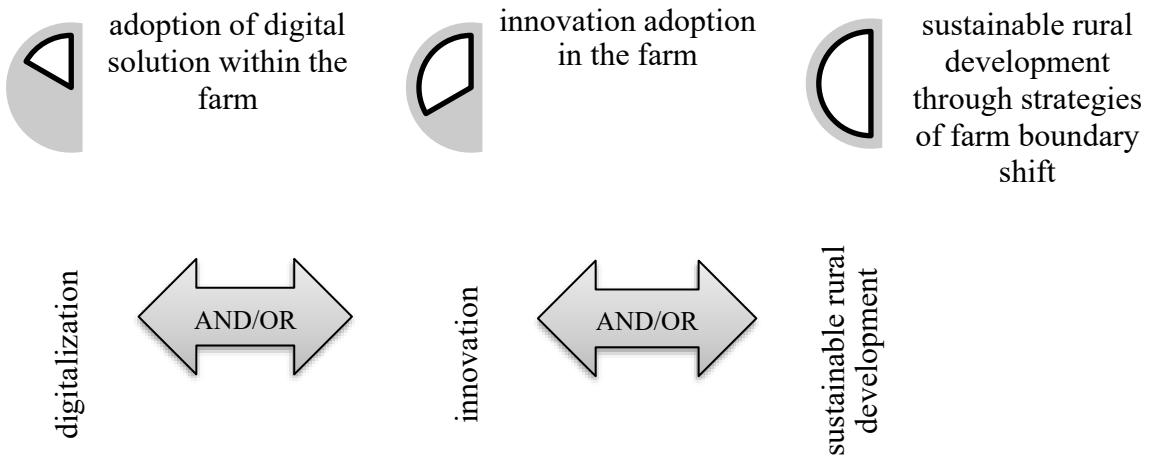

Figure 1. Digitalization–innovation–sustainable rural development nexus: A three-pronged approach.

The farms' strategies of sustainable rural development are framed within portfolio entrepreneurship [16], targeted to supporting territorial approaches to rural development [17]. These strategies are investigated through a double lens perspective, which includes the two main dimensions of multifunctional farming systems, focused on either deepening or broadening strategies [18–21]. Deepening strategies adopt a sectorial perspective by involving the agrifood supply chain through considering eventual differentiation strategies, such as adoption of organic farming. Broadening strategies account for the rural space and the adoption of diversification strategies synthesized by the presence of other gainful activities.

The results of the analysis reveal how the "disruptive" nature of digital innovation [6,22] may stimulate heterogeneous dynamics (no nexus vs three-pronged approaches), with consequent diversified impacts on the farming systems and (smart) rural development.

In order to analyze different trajectories and nexuses, a "context" lens is adopted. More precisely, heterogeneity is analyzed from a "context" perspective, as put forward by Welter [23]. By considering the multiplex facets of the context, business, social, and spatial contexts are analyzed.

In the following section, we present the methodology of analysis, based on the use of secondary sources, while in Section 3, we present the results of the empirical analysis. The paper will close with a discussion of the results and policy implications.

2. Materials and methods

The empirical analysis is drawn on secondary data extracted from the last Italian Census of Agriculture carried out by the Italian Institute of Statistics (ISTAT) [24]. The sample includes 226,668 farms and is limited to those that adopt either innovations or digital technologies or both. The aim of the analysis is to evaluate eventual strategic nexuses connecting innovation paths and digital transition with the presence of sustainable farming practices and extended strategies of territorial rural development [17,25].

Therefore, we have extracted the information by which it is possible to investigate the three-pronged nexus. More precisely, variables are extracted from Sections A, D, and F of the questionnaire, as shown in Table 1.

Table 1. Questions extracted from the ISTAT census of Italian agriculture.

	Questions extracted from the ISTAT census of Italian agriculture
Digitalization	F13: Does the farm use digital or ICT technologies?
	F14: For which purposes (accounting, organizational issues, market development, etc.)?
	F15: Does the farm use the internet?
Innovation	F16: In the last three years, did the farm adopt innovations?
	F17: For which purposes?
Sustainable rural development	A7: Does the farm use organic farming?
	A9: Is the farm converting to organic farming?
	D1: Does the farm carry out other gainful activities?
	Type of rural area (A, B, C, D, according to the national strategic plan)

ICT, information and communication technology.

More precisely, digitalization is considered through the access to information and communication technologies (ICTs) and to the farms' eventual use of the internet. More precisely, we have extracted information from the ISTAT questionnaire regarding the use of computers or other ICT and digital equipment for business purposes by farms. Additionally, we identified the specific activities for which farms use software solutions, such as accounting, administrative services, crop/livestock management, and the management of other gainful activities.

As far as innovation is concerned, from Section F, we have analyzed the uptake of innovations and the related purpose. More precisely, the extracted data allow us to explore the types of innovation adopted, such as those related to varieties, breeds, plant irrigation, fertilization, livestock housing, animal nutrition, milking, waste management, mechanization, buildings' structure and use, farm organization and management, product sales and marketing, and other gainful activities.

Finally, in order to analyze sustainable farming practices and extended rural development [26], we have drawn our analysis on van der Ploeg et al's boundary shift model, considering either deepening or broadening strategies [18]. Diversification of agricultural activity can be realized in farm-related activities or in farm diversification (for instance, agritourism).

Moreover, the farm's territorial localization is taken into account to point out examples of the extended territorial strategy bringing about sustainable development paths in particular areas, such as rural remote areas, as classified by the strategic plan for common agricultural policies. Therefore,

belonging to areas classified as D provides strength to the territorial extended strategy.

The related variables have been created in two steps.

1. The first step investigates the use of digital innovation or the adoption of innovation by the farms. More precisely, with the purpose of exploring the digitalization–innovation nexus, a new variable was created to assess whether farms adopt digitalization and/or innovations; this variable, called "digitalization and/or innovation", includes three modalities: digitalization only, innovation only, and both digitalization and innovation. Moreover, as far as innovation is concerned, the aforementioned data available from the dataset allow us to classify innovations into different typologies, such as technical or managerial/organizational innovations.
2. In the second step, the three-pronged nexus (digitalization–innovation–sustainable farming and rural development) is analyzed. To this end, we selected the following variables related to the impact on sustainable farming practices and rural development. As far as sustainable farming is concerned (deepening strategies), we have selected variables related to the presence of organic or conversion to organic farming practices, which can be considered as indicators of the adoption of agronomically sound agricultural practices. This choice could represent a limit of the analysis, as sustainable farming is limited to the adoption of organic agriculture. Regarding sustainable rural development, the adoption of diversification strategies at farm level and localization in specific areas classified by the national plan for rural development are considered to be broadening strategies. As far as diversification strategies are concerned, other gainful activities are considered from the available variables of the Italian census. These strategies include diversification into farm-related and farm diversification activities. Moreover, the farms' localization is also taken into account under the hypothesis that the presence of digitalization–innovation nexus in the remote rural context (Area D) has great impact on the promotion of smart rural development as underlined in the long-term vision for rural areas, addressing the development of strategies focused on strong, prosperous, connected, and resilient rural areas [27].

Accordingly, different types of nexuses can be discovered as shown in Table 2.

Table 2. Classifying the nexuses.

The following potential nexuses can be discovered		
✓	No nexus	Only digitalization, or innovation, or sustainable farming
✓	DSA = dual-sector approach	For instance, digitalization + innovation
✓	TPA = three-pronged approach	Digitalization + innovation + sustainable farming practices or other gainful activities
✓	MPA = multi-pronged approach	Digitalization + innovation + sustainable farming systems and other gainful activities

In order to classify the farms according to the typology of nexuses, we conducted a multivariate analysis (using SPAD software), made up of a multiple correspondence analysis (MCA) and a cluster analysis (CA) via a mixed (both hierarchical and nonhierarchical) method [28,29].

MCA is commonly used with the purpose of investigating the relationships among multiple categorical variables. More precisely, MCA allows us to reduce dimensionality through simplifying complex data and identifying the patterns of relationships among qualitative variables. Accordingly, the method allows us to extract the main factors that contribute to the shaping of the clusters. The

MCA method presents limitations when used with census data, such as potential biases related to self-selection, and a lack of dynamic variables. Nonetheless, it has been considered a valid approach for identifying a synthetic number of factors to process in the subsequent cluster analysis.

The following CA permits us to pinpoint homogeneous groups of farms according to the results of the MCA. More precisely, the objective of the CA is to group statistical units into clusters that are characterized by the maximum homogeneity within the same groups and by the maximum heterogeneity amongst different groups. This allows us to clearly distinguish groups of farms on the basis of the presence of different degrees of connection (digitalization–innovation–sustainability), which is the purpose of our paper.

Clustering of the statistical units is carried out using a mixed method, starting with a nonhierarchical method, which is later integrated with a hierarchical method. The choice of the optimal number of clusters is realized by cutting the tree-like diagram (the dendrogram) where the branches are longer, i.e., where the internal groups' variance starts increasing. The dendrogram analysis was carried out by considering the relationship between analysis and synthesis and then choosing the partition that best met the research's objectives. The selected partition was able to highlight the differentiating and characterizing elements of the groups, which optimally addressed the study's hypotheses and objectives.

Therefore, 19 active categorical variables contributed to the building of the homogenous clusters, while 34 supplementary categorical variables were useful for better describing the resulting clusters (through their positioning in the factorial space). The variables are presented in Table 3, specifying the active and the supplementary ones: Active variables contribute to identifying the clusters, while supplementary variables provide relevant information to characterize the homogeneous groups of farms.

Table 3. Discrete context variables used in the empirical analysis.

Type of context	Variables
Business	Utilized agricultural area (active), livestock units (active), standard output (active), types of farming (active), other on-farm and off-farm activities (active), passive subcontracting (supplementary)
Social	Associationism (active), farmer's age (active), farmer's level of education (active), farmer's gender (active), number of days worked by the farmer (active), training programs joined by the farmer (active), organic farming (supplementary).
Spatial	Types of rural areas (active), altimetric zone (supplementary)

3. Results

3.1. Multiple correspondence analysis

The MCA conducted with the abovementioned variables led to the generation of four factorial axes explaining 94% of the variance, which were re-evaluated using Benzècri's reweighted formula [30]; these axes can be briefly described as follows.

Factor 1 identifies the structural characteristics of the farms. It contrasts farms with smaller and with greater physical and economic dimensions.

Factor 2 depicts the farms' adoption of innovation: It contrasts farms that do not innovate at all with

farms adopting one or more innovations.

Factor 3 specifies the presence of digitalization and/or innovation, contrasting farms adopting only digital solutions and farms only adopting innovations without digitalization.

Factor 4 indicates the territorial localization of the farms, contrasting farms in remote rural areas and farms in areas with specialized and intensive agriculture.

3.2. Cluster analysis

According to the analysis of the dendrogram, the CA clearly identified five groups of homogeneous farms (Figure 2).

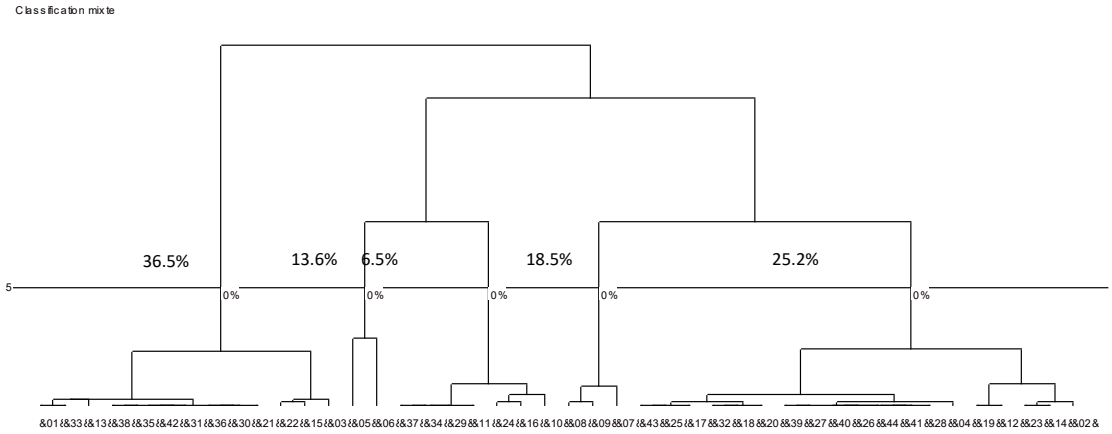

Figure 2. Clusters extracted from the analysis (percentage values).

In Table 4, we have synthesized the main characteristics of each cluster, highlighting any nexuses found. The table shows a high degree of heterogeneity, with a diversified set of relationships among the analyzed variables.

Table 4. Characteristics of the clusters and presence of nexuses.

	No. of farms	Presence of a nexus
Cluster 1	88,332	Only digitalization – no nexus
Cluster 2	30,842	Three-pronged nexus
Cluster 3	14,662	Dual-sector nexus (digitalization + innovation)
Cluster 4	41,816	Only innovation – no nexus
Cluster 5	57,016	- Dual sector nexus (digitalization + innovation) - Multi-pronged approach

Cluster 1 includes 88,332 farms and accounts for 36.3% of all sample, predominantly located in intermediate rural areas (*t*-test = 26.36) and, to a lesser extent, in urban areas (*t*-test = 15.33) or areas with intensive agriculture (*t*-test = 7.11). Farms declared that they use digital technologies (*t*-test = 444.73), while they declared that they do not innovate (*t*-test = 444.73). Neither diversification strategies nor organic farming have been adopted. Farms in this cluster are quite small: Half of them

have a standard output lower than € 25.000,00. Moreover, they are more specialized in arable and permanent crops, with no animal farming (*t*-test = 154.93).

Cluster 2 includes 30,842 farms, making up 13.6%. These farms are characterized by the presence of a three-pronged approach (digitalization + innovation + sustainable rural development). Farms grouped in Cluster 2 are full-time farms specialized in breeding herbivores (*t*-test = 281.21); 60.51% of the farms are located in remote rural areas (Area D) (*t*-test = 126.99), 46.48% of which are in mountainous areas (*t*-test = 103.99). In this cluster, the three-pronged nexus is fully verified, in that the farms display both digitalization (*t*-test = 137.53) and innovation (*t*-test = 43.28), which may support diversification strategies (*t*-test = 34.86), through either on-farm or off-farm diversification, aimed to empower multifunctional agricultural systems.

Cluster 3 is made up of 14,662 farms (6.5%), showing a dual-sector nexus (digitalization–innovation). These farms are mainly located in areas with specialized and intensive agriculture (*t*-test = 85.27) in northern Italy (*t*-test = 75.45). More precisely, Cluster 3 is made up of animal farms (*t*-test = 287.25) that operate within conventional farming systems, with the adoption of digital technologies for supporting the management of animal farms (*t*-test = 154.81), and with high rates of adopting innovation (*t*-test = 74.88). Moreover, farms in this cluster are characterized by the presence of intensive livestock farming, with 86.5% of farms having more than 100 livestock units, and with a large share of farms with a standard output higher than €500.000,00 (*t*-test = 203.19).

Cluster 4 (41,816 farms; 18.5%) includes farms with no nexus; only the presence of innovation is discovered. Actually, this cluster is distinguished by the absence of any kind of digitalization (*t*-test = 340.75). Nonetheless, these farms have adopted innovations (*t*-test = 239.76). The innovativeness of farms is principally reflected in the crops, with special reference to innovative solutions for the mechanization of farming activities (*t*-test = 88.52). No other gainful activities are adopted (*t*-test = 88.13). As far as structural characteristics are concerned, farms grouped in Cluster 4 typify farming systems with small farms, managed by old farmers (*t*-test = 87.34) with low levels of education and no relational assets (no adhesion to collective farmer marketing initiatives) (*t*-test = 52.73). Most of the farms are on hills (49.7%) (*t*-test = 34.89) and located in intermediate rural areas (42.4%).

Cluster 5 includes 25.2% of total farms (57,016 farms) and is characterized by the presence of farms with a dual-sector nexus (digitalization + innovation). However, a potential transition towards a multi-pronged approach is discovered in some of these farms (innovation + digitalization + investments in other gainful activities + sustainable farming). More precisely, farms in Cluster 5 adopt innovations (*t*-test = 327.92) and use digital technologies (*t*-test = 288.49). Numerous innovations have been adopted in the last years by the farms in this cluster (*t*-test = 158.74). Moreover, some farms in this cluster are investing in farm diversification strategies (*t*-test = 73.15) and organic farming (*t*-test = 46.29). For most of the farms, digital tools are used for business purposes (89.7%), and software packages are used for administrative services (73.3%) and for crop management (34.3%). At the same time, the innovations adopted are also strongly concentrated on aspects of the farm related to cultivation (60.3%) and business organization (10.5%). The farms are prevailingly managed by young farmers.

4. Discussion and conclusions

The three-pronged approach here has been explored through the help of secondary sources and allowed us to explore, in greater depth, the potential impact of digitalization and innovation in building up sustainable farming practices and smart rural development processes. Future research is necessary

to better excavate the nexuses, especially with the support of primary sources, which may enable a wider comprehension of the nexus thinking perspective. This would allow a better comprehension of the determinants of adopting enabling technologies, which may suggest alternative and integrated approaches for a sustainable transition [4].

Despite these limits, from our analysis, interesting insights emerge. The sustainability of agrifood systems and rural embeddedness through the activation of diversification strategies strongly rooted in rural contexts (like areas classified as D) set up the basis for alternative and sound business models grounded on the idea of either weak or, most importantly, strong multifunctionality [31]. In Figure 3, we have synthesized the results of our analysis within a dynamic perspective highlighting the transition towards smart rural development processes, read through the lens of the nexus approach.

The context lens is sound in revealing the heterogeneity in the adoption of digital solutions, innovation, and strategies of sustainable farming and rural development. Nonetheless, the study shows some limits related to the use of secondary data and the use of organic farming as a proxy variable for sustainable farming practices. Therefore, further research is needed to better examine the nexuses and to shed light on the institutional context in which farms operate, as it is not considered in this study. Despite these limits, we believe the analysis provides useful insights if read through the lens of the three-pronged nexus adopted in this paper.

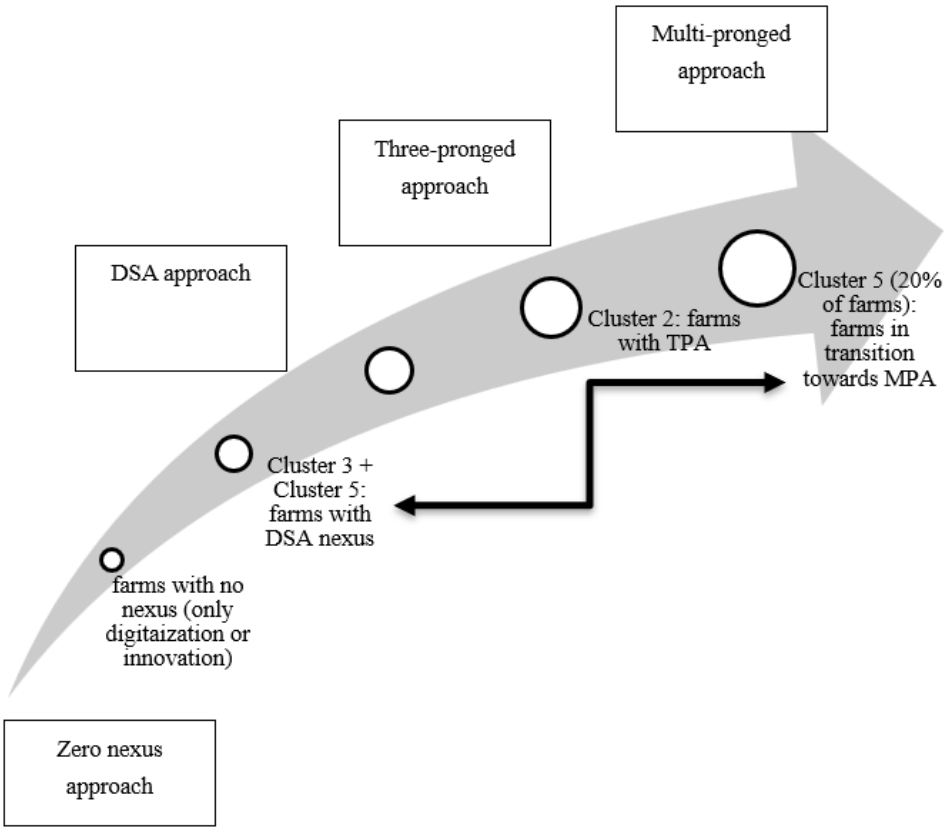

Figure 3. Different dynamics and nexuses.

As a matter of fact, three main types of nexuses are highlighted. In the first one, the digitalization–

innovation–sustainable rural/agricultural development nexus clearly emerges and depicts two different strategies. The first, adopted by farms in Clusters 2 and 5, is a territorial strategy widely explored in the literature [26], which indicates a sound entrepreneurial approach which is functional to strengthening rural communities and landscape management (particularly in areas classified as D, characterized by complex problems of development), thanks to the implementation of strategies of diversification carried out through on- and off-farms diversification into farm-related and farm diversification activities [16]. Digitalization encourages innovations aimed to promote smart rural development and to increase the degree of multifunctionality in the farming systems in remote rural contexts, thus improving the quality of life of local rural communities [2]. Our results are congruent with the idea that, notwithstanding the vicious circle of rurality in which they are trapped, farms located in marginal rural areas contribute to the local development of those areas, confirming that they have the potential to obtain advantages and benefits from digital transformation [32]. Set against this background, our analysis confirms previous studies pointing out that digitalization and innovation may represent the engine to boost new paths of sustainable rural development [11,33], particularly in inner areas [34]. Empirical analysis shows that the digitalization–innovation nexus emphasizes new "disruptive" technologies aimed at boosting sustainable farming systems and smart rural development, with a high impact on agricultural and rural local communities. Moreover, the dynamics found in remote rural areas are coherent with the long-term vision for rural areas [27]: Having 'digitally connected' rural areas by 2040 will somewhat favor the adoption of innovations in those areas. The second entrepreneurial strategy is grounded on sustainable agrifood systems, where the digitalization–innovation nexus is functional for pursuing the adoption of various innovations (product/process/organizational) aimed at strengthening differentiation strategies based on organic and/or conversion to organic farming practices (Cluster 5), particularly in farms specializing in crops and located in areas with intensive agriculture or in urban/periurban contexts. Therefore, farms in this group are oriented towards digitalization and innovations serving the transition towards sustainable farming systems. Moreover, digitalization engenders new communities of practice [35], as demonstrated by the high rates of membership in farmers' cooperatives or producers' organizations.

The second type of nexus is a dual-sector approach and concerns only the digitalization–innovation nexus. This nexus confirms the literature on the role of digital technologies in boosting farms' efficiency [36], and is consistent with productivity strategies aimed to consolidate entrepreneurial strategies within the agro-industrial paradigm [26], where the digitalization–innovation nexus is functional for pursuing efficiency logics within a globalized mode of food provisioning (Cluster 3), mainly in the livestock sector, particularly in the intensive animal farms located in the lowland areas of northern Italy. Consequently, the choice of digitalizing and innovating is adopted within a well-identified and conventional business model.

In the third type, the nexus is not working at all. More precisely, the first group of farms (Cluster 1) adopts digital solutions, but they have introduced no innovations in the last three years. In this case, the nexus between the introduction of other innovations and farms with digital technologies cannot be taken for granted; as a consequence, the analysis demonstrates how digitalization is not a sine qua non condition for innovation, given the variety of dimensions and contexts that characterize innovation. A second group of farms (Cluster 4) shows innovative characteristics but without digitalization. Innovation is mainly targeted to represent the level of farm mechanization, thus generating higher levels of production efficiency. The lack of technological infrastructure [37] seems to limit the adoption of further innovations.

Against the backdrop of the aforementioned heterogeneous scenario, rural policies play a relevant role. As clearly stated in the long-term vision for rural areas 2040 [27], the further development of rural areas is dependent on them being well connected between each other and to periurban and urban areas. Digital connectivity, sustainable food production, and diversification of economic activities are key pillars of the long-term vision. Our analysis also emphasized potential connections among these strategies through three-pronged approaches, which could be replicated at policy level. More precisely, the current rural policies for 2023–2027 support, on one hand, the adoption of innovative and digital solutions through investments aimed to encourage farms' competitiveness. On the other hand, funding for infrastructure investments and digital services is also expected to strengthen farms and to boost the socioeconomic development of rural areas. Finally, "traditional" interventions for diversifying farming activities in rural contexts, through empowering multifunctional agriculture, are key drivers to stimulate sustainable rural development. Accordingly, a nexus perspective could also be encouraged through the effective support of farm advisory services, which may encourage access to a diversified set of measures, with the purpose of triggering smart rural development strategies. However, it is also necessary to incentivize farms to obtain the minimum (digital) technological requirements for adopting an innovation, which could accelerate the transition towards more diversified and digitalized rural areas.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

All authors contributed equally to the manuscript.

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