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# Social network analysis of Tunisia's wheat seed system: from centralized structures to inclusive and adaptive governance

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Tunisia's wheat seed system faces structural and institutional constraints that limit its performance, resilience, and contribution to food sovereignty under climate variability and import dependence. This study applies a functional Social Network Analysis to examine actor interactions and identify leverage points for systemic improvement. 25 semi-structured interviews were conducted with actors from public institutions, the private sector, research institutions, and professional organizations to capture institutional knowledge and practical perspectives. Results reveal a highly centralized network dominated by public institutions, notably the Cereals Office and the General Directorate of Agricultural Production. While centralization ensures national coherence and strategic coordination, it limits local adaptability, inclusiveness, and innovation adoption. Territorial actors, including agricultural services, farmers' organizations, cooperatives, and seed collectors and distributors, occupy marginal positions, weakening feedback loops essential for responsive decision-making and context-adapted seed dissemination. These patterns highlight critical governance trade-offs, where centralization supports efficiency and national coordination but concurrently constrains inclusion, local empowerment, and resilience. The enhancement of the performance of the wheat seed system necessitates the implementation of formalized participatory governance, the consolidation of the capacities of local actors, and the integration of digital platforms to optimize the flow of information and enable the provision of timely feedback. Complementary mechanisms, including diversified financing instruments and structured public-private partnerships, are also crucial to sustain certified seed production and adoption. By linking actor positions, network structure, and governance dynamics to policy pathways, this study provides actionable insights for institutional innovation, adaptive management, and resilience. The findings provide transferable lessons for the enhancement of wheat seed systems in Tunisia and similar MENA contexts. The findings also demonstrate the relevance of Social Network Analysis for guiding strategic decision-making, multi-actor coordination, and sustainable seed system investments.

### KEYWORDS

food security, leverage points, multi-actor governance, policy instruments, social network analysis, Tunisia, wheat seed system

## 1 Introduction

The Middle East and North Africa (MENA) region faces persistent and multifaceted food security challenges, driven by rapid population growth, structural dependence on food imports, and limited natural resources (Kozielec et al., 2024). Chronic water scarcity, exacerbated by climate variability and geopolitical instability, further constrains agricultural production, positioning the region among the least self-sufficient globally (Le Mouël et al., 2023; El Bilali and Ben Hassen, 2024). Cereals constitute the backbone of both dietary habits and agricultural systems, with wheat emerging as the most strategic crop, contributing over 50% of caloric intake. However, local production satisfies only 30–40% of cereal demand, resulting in a structural dependence on imports (Rahimi et al., 2023; Devkota et al., 2025). This dependence heightens vulnerability to global shocks and underscores the urgency of strengthening Wheat Seed Systems (WSS) to improve yields, mitigate risks, and enhance food system resilience (Yigezu et al., 2021; Tita et al., 2025).

Seed systems encompass the institutions, actors, and processes engaged in the development, production, distribution, regulation, and adoption of quality seeds (Sperling and Cooper, 2003). In the MENA region, WSS exhibit both structural and functional limitations that undermine its efficiency and adaptability. These include centralized governance, fragmented value chains, limited public funding for both research and development, weak infrastructure for seed multiplication and storage, and rigid regulations that inadequately address farmers' needs (Bishaw et al., 2019; Tita et al., 2025). Such limitations constrain the dissemination of improved varieties and reduce the system's responsiveness to climate variability, technological change, and market signals (Dadrasi et al., 2023).

Tunisia illustrates these systemic challenges. Cereals occupy nearly 30% of cultivated land and employ almost half of the agricultural labor force. Wheat, both durum and bread, contributes around 50% of daily caloric intake and 64% of protein requirements (Rached et al., 2022; Chebbi et al., 2023), with cultivation concentrated in northern rainfed areas. Durum wheat covers 576,000 ha and bread wheat 24,000 ha, totaling around 700,000 ha (Direction Générale de la Production Agricole, 2024). Despite its strategic importance, Tunisia produces only a fraction of its wheat demand, importing nearly 1.6 million tons annually, exposing the country to price volatility and geopolitical risk (Thabet et al., 2024).

As indicated by Bouatrous et al. (2022) and Melki et al. (2024), factors such as soil degradation, inefficient water irrigation have led to constrained heat production. Additionally, socio-economic factors, including an aging farming population, limited technical capacity, and low adoption of certified seeds, have contributed to this phenomenon, as outlined by Guesmi et al. (2021) and Chebbi et al. (2023).

In 2023, certified cereal seed production totaled 30,000 tons (24,000 tons durum, 3,800 tons bread wheat), yet adoption remained below 20% nationally and 30% in irrigated areas or high-potential areas, well below the FAO's recommended benchmark of 30%. Over 80% of seeds are sourced from farm-saved or informal channels, highlighting the need to expand certified seed production and strength farmer-oriented extension services. This low adoption rate reflects multiple structural and functional constraints within the WSS (Hammami and Gharbi, 2018; Direction Générale de la Production Agricole, 2024).

The enhancement of the WSS has the potential to contribute to the consolidation of local autonomy, the facilitation of access to

certified seeds, and the reduction of dependence on imports. This, in turn, could have a beneficial impact on Tunisia and other countries encountering analogous structural and institutional impediments.

While existing studies on seed systems in developing countries, including those in the MENA region, have largely emphasized technical, economic and institutional dimensions (Yigezu et al., 2021; Bishaw et al., 2024; Tita et al., 2025), less attention has been paid to the relational dynamics that shape actor coordination, information flows, and governance system. These “soft” system components, such as collaboration patterns, knowledge exchange, and institutional interdependencies, are critical for understanding functional performance and resilience of seed systems.

Several methods are available to examine actor interactions within seed systems, including participatory mapping, stakeholder analysis, and institutional assessments (McGuire and Sperling, 2016; Suri and Gartaula, 2023). Among these, Social Network Analysis (SNA) offers a robust methodological framework for mapping and quantifying the relationships among seed system actors (Allipour Birgani et al., 2022; Barrera and Ibarra, 2024; Ouerghemmi et al., 2024). Unlike conventional actor-based approaches, SNA captures the structural complexity of multi-actor systems and uncovers hidden governance bottlenecks that can impede performance and innovation diffusion (Palonen, 2022; Wang, 2024).

This study applies SNA to analyze the functional structure of Tunisia's WSS. By mapping actor interactions across key function, such as information flow, supply coordination, and regulation, it identifies strategic actors, structural dependencies, and bottlenecks. The findings provide actionable insights to enhance WSS performance and resilience in Tunisia, while offering transferable lessons for similar MENA contexts on guiding strategic decision-making, multi-actor coordination, and sustainable seed system development.

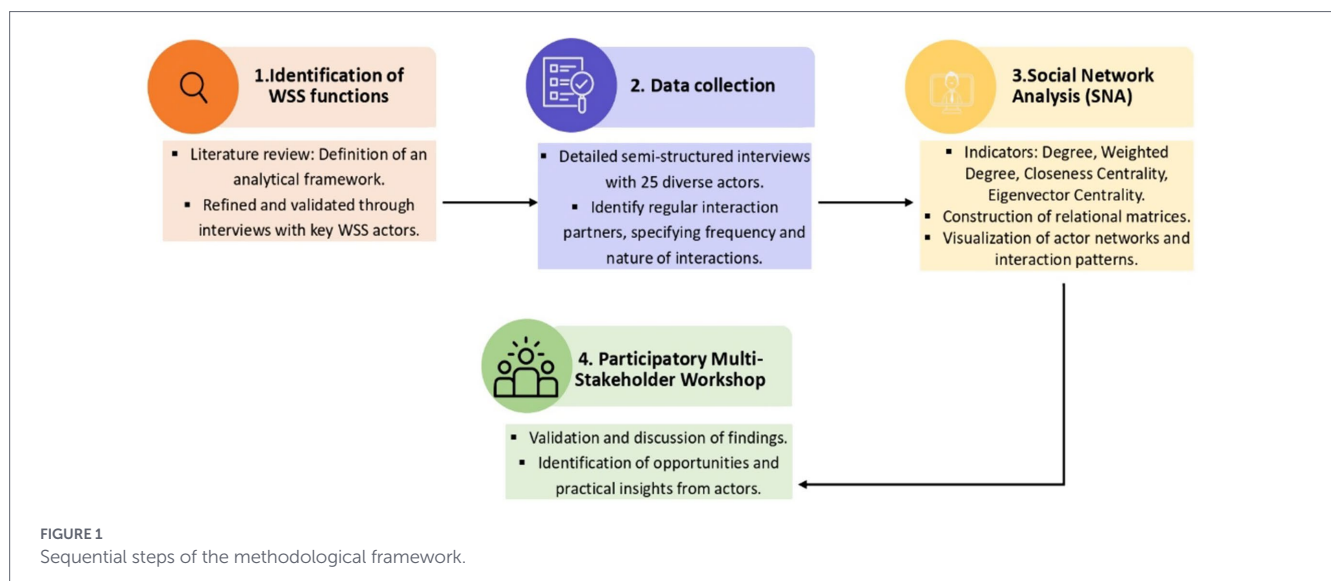
## 2 Methodology

This study adopts a qualitative and exploratory approach to assess the functional structure of Tunisia's WSS. The methodological framework is structured into four complementary steps (Figure 1).

First, a comprehensive literature review was conducted to establish the analytical framework, identifying key WSS functions and actor categories. Second, semi-structured interviews were conducted with a sample of actors of Tunisia's WSS to capture diverse perspectives and relational dynamics. Third, SNA was applied to systematically map and quantify interactions among actors, revealing network structure, coordination mechanisms, and governance bottlenecks. Finally, a participatory multi-stakeholder workshop was organized to validate results, refine network maps, and ensure the contextual relevance of findings.

### 2.1 Identification of the main functions of the wheat seed system

The functional structure of a WSS describes how roles, interactions, and processes, ranging from varietal development to seed adoption, are organized and coordinated among various actors. Unlike formal governance models that emphasize mandates and rules, a



functional perspective focuses on real-world processes, including **2.2 Data collection**

TABLE 1 Main functional domains of Tunisia's wheat seed system.

| Function   | Description  | References   |
|--|--|--|
| Governance, strategic planning, and administration | Covers the regulatory, institutional, and policy frameworks that govern the WSS. This includes variety release procedures, certification standards, pricing mechanisms, production targets, and incentive schemes.   | Spielman and Kennedy (2016) and Van De Gevel et al. (2020) |
| Access to information and knowledge sharing        | Refers to the availability and dissemination of information related to certified wheat seed demand, production, distribution, and pricing. Access to timely and accurate data enables better decision-making and anticipatory responses to market changes. | McGuire and Sperling (2016) and Bolfe et al. (2020)        |
| Awareness, training, and institutional support     | Covers activities aimed at informing and training actors about the benefits of certified seeds. It includes capacity-building initiatives and collaboration between public and private institutions.   | Pautasso et al. (2013) and Balogun et al. (2022)           |
| Financing, funding, and incentive mechanisms       | Includes financial instruments such as subsidies, credit schemes, and investment initiatives designed to support seed multiplication and improve farmer access to certified wheat seeds.   | Scoones and Thompson (2011) and Yigezu et al. (2021)       |
| Production and commercialization of wheat seeds    | Covers the entire wheat seed value chain, including breeder and foundation seed multiplication, certified seed production, quality control, processing, storage, and distribution to farmers.  | Donovan et al. (2021) and Teeuwen et al. (2022)            |

knowledge flows, decision-making, and power dynamics (Mulesa et al., 2021; Westengen et al., 2023).

In Tunisia, the main WSS functions were identified through a targeted literature review of peer-reviewed articles, institutional reports, and expert assessments. This review informed the construction of an initial analytical framework, which included categories such as varietal development, strategic governance, seed production, quality control, distribution, technical support, and farmer access. The framework was further refined through interviews with actors from public institutions, research institutions, private sector, and professional organizations. Table 1 presents the final set of functional categories, along with their operational definitions and relevant references.

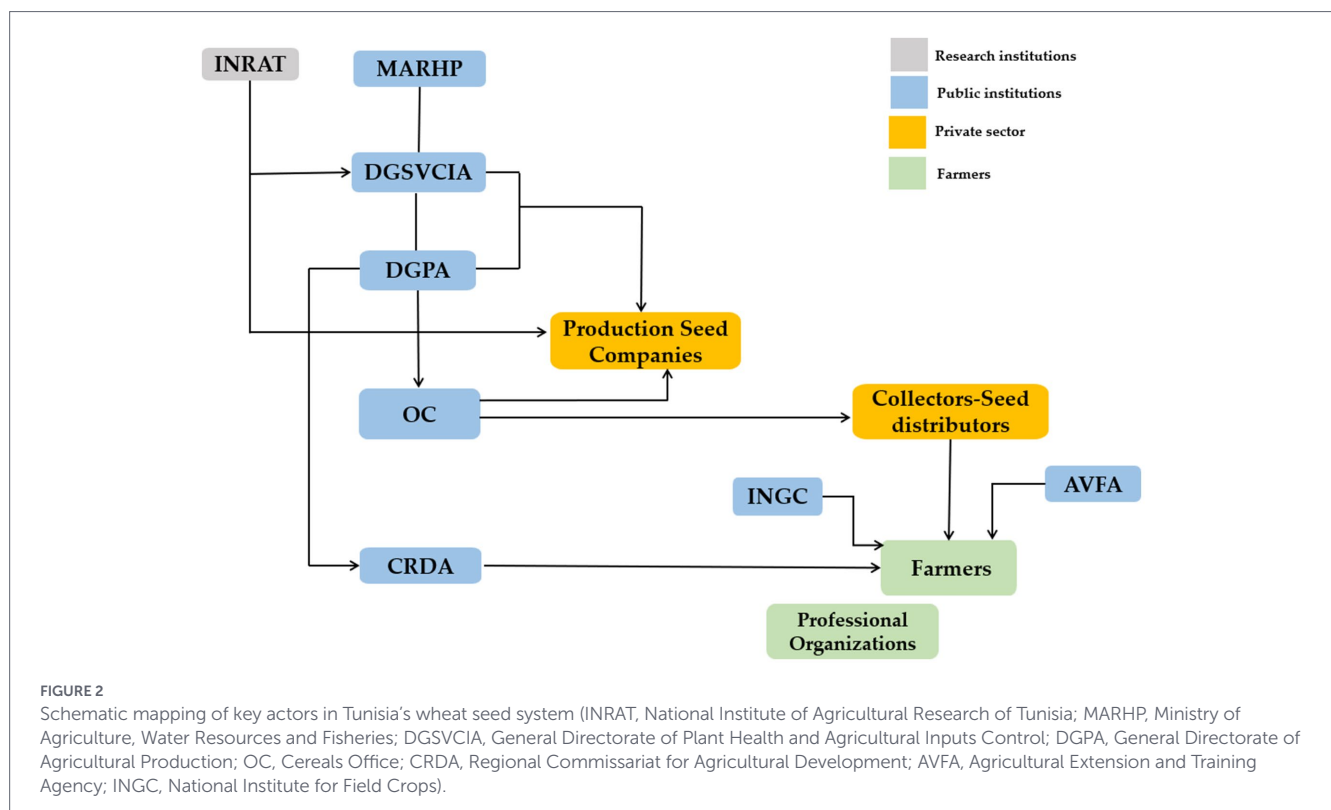
Building on these functional categories, a preliminary actor mapping was developed (Figure 2) to visualize the WSS structure. This mapping served as a reference point for interview sampling and for the design of the network analysis.

Data were collected through semi-structured interviews using a guide tailored to the diverse profiles of actors involved in Tunisia's WSS. Based on the actor mapping (Figure 2), 25 actors (15 men and 10 women) were purposively selected using criterion-based sampling to ensure representation across WSS functions and governance levels (Table 2).

The sample included representatives from public institutions, research institutions, private sector, and professional organizations. All interviewed farmers were also active members of collective entities such as SMSAs or GDAs, often serving in leadership roles.

The sampling strategy aimed to capture diversity in institutional type, geographical coverage (national, regional, local), and functional role, while limiting initial bias regarding actor centrality. The final sample size of 25 interviews was deemed sufficient to reach thematic saturation and map key interaction patterns.

In centralized institutions such as the DGPA and OC, one representative per organization, or a synthesis of multiple inputs, was selected reflecting their unified mandates and centralized



decision-making structures. In contrast, the private sector sample was more diversified, including 7 collectors–distributors (out of 23) and 3 seed production companies (out of 4), in order to capture heterogeneity in capacity, business models, and regional coverage.

During the interviews, participants were asked to provide:

- i Functional involvement: describing their roles and activities within each the defined WSS functions (Table 1).
- ii Actor interactions: Identification of their key collaborators for each function, including actors outside the interview sample. For each interaction, participants indicated the interaction frequency (daily, weekly, monthly, 2–5 times/year, once/year or less) and the nature of the relationship (formal/informal; technical, financial, or institutional; unidirectional or reciprocal).

This structured information was used to build weighted relational matrices, capturing the intensity and characteristics of actor relationships across functions, a common approach in applied SNA studies.

### 2.3 Data analysis according social network analysis (SNA)

SNA provides a framework for understanding a group of actors by mapping the relationships that connect its members as a network. It enables the identification of key groups within the network and the analysis of interactions among actors (Bahri and Widhyharto, 2021; Allipour Birgani et al., 2022).

Networks consist of nodes (actors) connected by ties or links, often visualized through sociograms. SNA focuses on describing relationships between actors and examining their effects at both the

network and individual levels (Prota et al., 2018; Allipour Birgani et al., 2022).

The SNA was conducted using Gephi (version 0.10.1), an open-source software widely used for network visualization and analysis.

The results were interpreted based on main indicators, calculated using the following formulas:

- Degree ( $v$ ) =  $\sum_{u \in V} A_{vu}$ ;  $A$  is the adjacency matrix, and  $A_{vu} = 1$  if there is an edge between node  $v$  and node  $u$ , and 0 otherwise. It measures the number of direct connections a node has, reflecting its level of integration and participation within the network.
- Weighted Degree ( $v$ ) =  $\sum_{u \in V} w_{vu}$ ;  $w_{vu}$  is the weight or the frequency of the edge between node  $v$  and node  $u$ . It accounts for the strength or intensity of ties, indicating how actively an actor interacts with its partners.
- Closeness Centrality ( $v$ ) =  $\frac{1}{\sum_{u \in V} d(v,u)}$ ;  $d(v,u)$  is the shortest distance between node  $v$  and node  $u$ . It evaluates how close a node is to all others in the network, capturing its ability to quickly access or disseminate information and resources.
- Eigenvector Centrality ( $v$ ) =  $\frac{1}{\lambda} \sum_{u \in V} A_{vu} \cdot EC(u)$ ;  $\lambda$  is a constant (the largest eigenvalue of the adjacency matrix  $A$ ) and  $EC(u)$  is the eigenvector centrality of node  $u$ . It measures a node's influence based on its connections to other highly connected nodes, highlighting its strategic and prestigious role within the network.

Actors were assigned to their primary functional domain (Table 1), allowing for both general and function-specific network

TABLE 2 Characteristics of interviewed stakeholders in Tunisia's wheat seed system.

| Stakeholder category       | Interviewed stakeholders                                       | Description   | Geographical scale <sup>a</sup> | Number of interviews |
|----------------------------|--|---|---------------------------------|----------------------|
| Public Institutions        | General Directorate of Agricultural Production (DGPA)          | Central governmental body responsible for developing and implementing national policies and strategies for agricultural production.                 | National                        | 1                    |
|                            | Cereals Office (OC)  | Public agency regulating cereal markets, managing strategic grain reserves, and supporting the development of cereal value chains.                  | National                        | 1                    |
|                            | Agricultural Extension and Training Agency (AVFA)              | Public agency offering technical training and extension services to farmers and agricultural professionals to promote productivity and innovation.  | Regional/Local                  | 1                    |
|                            | National Institute for Field Crops (INGC)                      | Technical institution responsible for the development and dissemination of best practices in cereal and field crop production.                      | National/Regional               | 2                    |
|                            | Regional Commissariat for Agricultural Development (CRDA)      | Decentralized authority tasked with implementing national agricultural policies and providing technical support at the regional level.              | Regional/Local                  | 4                    |
| Private Sector             | Collectors- distributors                                       | Actors involved in aggregation and storage of cereals, and seed distribution within the value chain.  | Regional /Local                 | 7                    |
|                            | Seed companies   | Enterprises ensuring the multiplication, certification, and distribution of certified seeds of cereals.   | Regional/Local                  | 3                    |
| Professional Organizations | Mutual Agricultural Service Companies (SMSA)                   | Farmer-led cooperatives providing shared services such as inputs, equipment rental, and technical assistance.                                       | Local                           | 2                    |
|                            | Agricultural Development Groups (GDA)                          | Non-profit community-based organizations supporting local agricultural development through resource mobilization, training, and cooperative action. | Local                           | 2                    |
| Research Institutions      | National Institute of Agricultural Research of Tunisia (INRAT) | Public research institution for agricultural innovation, varietal improvement, and scientific support to national policies.                         | National/Regional               | 2                    |
| Total                      |  |   |                                 | 25                   |

<sup>a</sup>National = Actors whose mandate, influence, and activities extend across the entire country; Regional = Actors whose scope of action is limited to a specific governorate or group of governorates; Local = Actors operating at the community, municipality, or village level.

visualizations and metrics. Relational matrices were constructed to map interactions both within and across functions, highlighting key nodes, structural gaps, and coordination patterns.

## 2.4 Participatory multi-stakeholder workshop

To ensure relevance and accuracy, a multi-stakeholder validation workshop was conducted with representatives from key public institutions (OC, DGPA, CRDA, AVFA, INGC, INRAT), the private actors (seed companies, collectors-distributors), and professional organizations. Participants reviewed the functional framework, discussed the observed network patterns, and reflected on emerging constraints and opportunities. This process grounded the analysis in practitioner realities, strengthened its empirical robustness, and enhanced the legitimacy of proposed recommendations.

## 3 Results: functional structure and network dynamics of Tunisia's wheat seed system

The Social Network Analysis results are organized according to the functional domains of the WSS, revealing the roles of actors within each function and the strength and patterns of their interactions.

### 3.1 Governance, strategic planning, and administration

The SNA results (Table 3; Figure 3) indicate that the OC and DGPA have the highest interaction levels, connecting with 12 and 9 actors, respectively, with weighted degrees of 67 and 62, reflecting frequent and intensive interactions. The CRDA interacts with 7 actors, with a weighted degree of 13, indicating a more localized coordination role. Closeness centrality further highlights the strategic positions of OC (0.739) and DGPA (0.586), while CRDA is moderately lower (0.548).

The OC and DGPA occupy central positions in the WSS, directing decision-making, regulation, and institutional coordination. The OC regulates the certified seed market, ensuring quality and managing procurement and distribution, while coordinating grain collectors, seed distributors, and seed companies to deliver wheat varieties with national production targets and regional agroecological conditions. The DGPA directs seed production targets, supervises multiplication with seed companies, implements incentives for certified seed adoption, enforces regulations, monitors production, manages storage, and allocates seed quotas across governorates in collaboration with the CRDA. At the regional level, the CRDA coordinates seed availability and distribution according to farmers' and collectors-distributors' demand, ensuring alignment with available varieties and local agroclimatic conditions. The functional differentiation underscores the strategic influence of regional and intermediary actors in linking national policies to local implementation.

Seed companies operate across the WSS value chain, from production and certification to distribution, while ensuring regulatory compliance. They interact with 3 to 5 actors, including the DGPA,

DGSVCIA (a public institution overseeing plant health standards, seed quality, and certification), INRAT and OC, with weighted degrees of 47 and 27, and closeness centrality scores of 0.566 and 0.500. Their participation in national and regional commissions, alongside public institutions (OC, DGPA, CRDA), highlights their strategic role in coordination operations and information flows. These positions demonstrate that seed companies act as critical intermediaries, bridging national-level directives with regional implementation.

Collectors-distributors, including service companies and authorized points of sale, operate locally to supply seeds to farmers while maintaining an intermediary role between national institutions and end-users. They interact with an average of 3 actors, notably the CRDA, OC and professional organizations, occasionally with the DGPA. Their weighted degrees, ranging from 22 to 31, reflect moderate but significant interactions, while closeness centrality of 0.480 indicates an intermediate yet strategically important position, enabling them to link OC with farmers. These intermediary actors play a key role in bridging national directives and local seed distribution, despite their lower formal rank.

While OC and DGPA remain central, the SNA reveals structural dependencies and coordination bottlenecks, identifying the CRDA, seed companies, and collectors-distributors as key leverage points to strengthen regional coordination, improve information flows, and enhance certified seed adoption. Peripheral actors, including DGFIOP (a public institution responsible for agricultural investment policies, subsidies, and coordination with professional organizations), DGSVCIA, and INRAT, exhibit low connectivity, with degrees between 3 and 4, weighted degrees ranging from 10 to 15, and closeness scores of 0.414 to 0.472, reflecting limited involvement in strategic governance decisions.

### 3.2 Access to information and knowledge sharing

SNA results (Table 3; Figure 4) reveal dense collaboration around the OC and CRDA. The OC interacts with 13 actors, with a weighted degree of 94, while the CRDA interacts with 10 actors, with a weighted degree of 117, reflecting their pivotal roles in disseminating information within the WSS. The DGPA interacts with 9 actors (weighted degree 91), occupying an intermediate but strategically significant network position. Large-scale collectors-distributors interact with 9 actors (weighted degree 62), while medium-scale groups have lower connectivity (weighted degrees 63 and 35), reflecting more localized roles. Notably, weak direct interaction between DGPA and CRDA points to potential bottlenecks in vertical information flow, highlighting areas where coordination could be strengthened.

The DGPA and large-scale collectors-distributors exhibit high closeness centrality (0.850 and 0.701, respectively), reflecting their structurally important positions in the information network. They act as critical bridges, linking WSS segments and facilitating information flow. The lack of a direct connection between DGPA and OC indicates a potential bottleneck in vertical information exchange among central actors.

The OC serves as a central hub in the information network, connecting extensively with producers and collectors-distributors. It enhances seed market transparency by publishing data on certified seed availability, governorate quotas, and official pricing, allowing downstream actors to anticipate supply, adjust purchasing, and plan

TABLE 3 SNA results by functional category for the Tunisian wheat seed system.

| Function   | Actor                                     | Degree | Weighted Degree | Closeness Centrality | Eigenvector Centrality |
|--|---|--------|-----------------|----------------------|------------------------|
| Governance, strategic planning, and administration | OC  | 12     | 67              | 0.739                | 1                      |
|  | DGPA                                      | 9      | 62              | 0.586                | 0.940                  |
|  | Seed Companies (formerly cooperatives)    | 5      | 47              | 0.566                | 0.645                  |
|  | CRDA                                      | 7      | 13              | 0.548                | 0.790                  |
|  | Seed Companies                            | 3      | 27              | 0.5                  | 0.440                  |
|  | Collectors-distributors (large-scale)     | 3      | 31              | 0.485                | 0.532                  |
|  | Collectors-distributors (medium-scale A)  | 3      | 22              | 0.482                | 0.532                  |
|  | Collectors- distributors (medium-scale B) | 3      | 22              | 0.480                | 0.440                  |
|  | DGFIOP                                    | 4      | 10              | 0.472                | 0.244                  |
|  | DGSVCIA                                   | 3      | 15              | 0.435                | 0.300                  |
|  | INRAT                                     | 3      | 10              | 0.414                | 0.350                  |
| Access to information and knowledge sharing        | OC  | 13     | 94              | 1                    | 0.6875                 |
|  | CRDA                                      | 10     | 117             | 0.988                | 0.594                  |
|  | DGPA                                      | 9      | 91              | 0.850                | 0.536                  |
|  | Collectors-distributors (large-scale)     | 9      | 62              | 0.701                | 0.595                  |
|  | Collectors-distributors (medium-scale)    | 5      | 63              | 0.588441             | 0.478261               |
|  | Collectors- distributors (medium-scale)   | 5      | 35              | 0.578338             | 0.5                    |
|  | INRAT                                     | 4      | 57              | 0.557                | 0.468                  |
|  | Seed Companies (formerly cooperatives)    | 5      | 35              | 0.541585             | 0.488889               |
|  | Seed Companies                            | 4      | 25              | 0.491371             | 0.468085               |
|  | INGC                                      | 2      | 14              | 0.277085             | 0.44                   |
|  | DGSVCIA                                   | 2      | 10              | 0.168947             | 0.34375                |
|  | AVFA                                      | 1      | 7               | 0.116776             | 0.37931                |
|  | DGFIOP                                    | 2      | 19              | 0.070786             | 0.366667               |
| Awareness and training                             | CRDA                                      | 15     | 165             | 1                    | 0.727                  |
|  | AVFA                                      | 11     | 164             | 0.821                | 0.648                  |
|  | INRAT                                     | 9      | 88              | 0.701                | 0.585                  |
|  | INGC                                      | 8      | 88              | 0.675                | 0.571                  |
|  | Collectors-distributors (large-scale)     | 7      | 69              | 0.583389             | 0.55814                |
|  | Collectors-distributors (medium-scale)    | 8      | 72              | 0.582769             | 0.55814                |
|  | Seed Companies (formerly cooperatives)    | 6      | 99              | 0.538                | 0.521                  |
|  | SMSA                                      | 5      | 50              | 0.432342             | 0.521739               |
|  | GDA                                       | 5      | 68              | 0.431528             | 0.521739               |
|  | Seed Companies                            | 4      | 28              | 0.466558             | 0.48                   |

(Continued)

TABLE 3 (Continued)

| Function                           | Actor                                  | Degree | Weighted Degree | Closeness Centrality | Eigenvector Centrality |
|------------------------------------|--|--------|-----------------|----------------------|------------------------|
| Financing and incentive mechanisms | OC                                     | 7      | 65              | 1                    | 0.631                  |
|                                    | BNA                                    | 5      | 31              | 0.723                | 0.541                  |
|                                    | Another Bank                           | 4      | 36              | 0.613                | 0.513                  |
|                                    | Collectors- distributors (large-scale) | 3      | 36              | 0.610                | 0.500                  |
|                                    | Seed Companies (formerly cooperatives) | 2      | 24              | 0.514                | 0.500                  |
|                                    | Collectors-distributors (medium-scale) | 2      | 10              | 0.514838             | 0.5                    |
|                                    | Seed Companies                         | 2      | 24              | 0.364123             | 0.461538               |
|                                    | DGFIOP                                 | 2      | 36              | 0.202011             | 0.387097               |
| Production and commercialization   | Seed Companies                         | 8      | 117             | 1                    | 0.560                  |
|                                    | Seed Companies (formerly cooperatives) | 7      | 54              | 0.829                | 0.522                  |
|                                    | Collectors-distributors (large-scale)  | 7      | 39              | 0.732                | 0.513                  |
|                                    | OC                                     | 7      | 107             | 0.725                | 0.500                  |
|                                    | Other farmers                          | 6      | 81              | 0.530                | 0.442                  |
|                                    | Seed Multiplier                        | 5      | 61              | 0.594                | 0.479                  |
|                                    | Collectors-distributors (medium-scale) | 4      | 24              | 0.594223             | 0.425926               |
|                                    | INRAT                                  | 5      | 60              | 0.32515              | 0.396552               |

production. The CRDA coordinates regional seed supply, collecting information on quantities, species, and varieties and transmitting it to the DGPA, ensuring allocations meet local demand and enhancing the WSS's adaptability and efficiency.

At the central level, the DGPA serves a key information hub, consolidating data from the CRDA and the National Agricultural Observatory (ONAGRI). It disseminates updated on seed availability, pricing, and potential surpluses or shortages, enabling both operational adjustments and policy guidance. The DGPA also channels information on improved species and varieties from INRAT and publishes national statistics on producers, cultivated areas, reinforcing its strategic role in evidence-based governance of Tunisia's WSS.

Collectors-distributors serve a critical intermediary role, conveying information on seasonal seed demand to producers and aggregating farmers' orders for the CRDA. This supports accurate regional planning and alignment between local demand and available seed supplies. Differences in network weight reflects actor profiles, with larger collectors occupying more central positions due to broader market coverage and stronger operational capacity, while smaller actors maintain localized connections. INRAT interacts with 4 actors, with a weighted degree of 57 and a closeness centrality of 0.557, reflecting its role as a knowledge-generation node. Its strong link with the CRDA facilitates the transfer of scientific information to farmers and allows for field-level feedback.

Former cooperative seed companies (notably the Central Seed Mutual Company – COSEM, which was the most frequently cited by interviewees) interact with 5 actors, with a weighted degree of 35, and closeness centrality of 0.542. Despite limited connectivity, INRAT and

these cooperative-based companies actively disseminate technical knowledge on variety types, crop management, and morphological traits, supporting informed decision-making among farmers and collectors-distributors. This illustrates that actors with moderate formal network positions can exert strategic influence by facilitating critical knowledge flows. In contrast, actors such as INGC, DGSVCIA, AVFA and DGFIOP occupy peripheral positions (Figure 3), with low centrality scores, indicating limited connectivity and reduced capacity to shape knowledge dissemination.

### 3.3 Awareness and training

SNA results (Table 3; Figure 5) indicate that the CRDA and AVFA are the most connected actors, interacting with 15 and 11 actors and displaying weighted degrees of 165 and 164, respectively. They occupy strategic positions in farmer support and awareness-raising, serving as central nodes for knowledge dissemination and coordination within the WSS. INRAT and INGC follow, connected to 9 and 8 actors with weighted degrees of 88, reflecting moderate but meaningful integration. Closeness centrality highlights their roles, with the CRDA at 1, AVFA at 0.821, and INGC and INRAT ranging from 0.675 to 0.701. These metrics indicate that CRDA and AVFA drive awareness and training initiatives, INRAT and INGC provide technical expertise reinforcing knowledge flows to farmers and intermediaries.

At the regional level, the CRDA, in collaboration with INRAT, INGC, collectors-distributors and AVFA, plays a key role in farmer awareness and support, promoting certified wheat seeds and best agronomic practices. Closely connected to farmers and aware of their

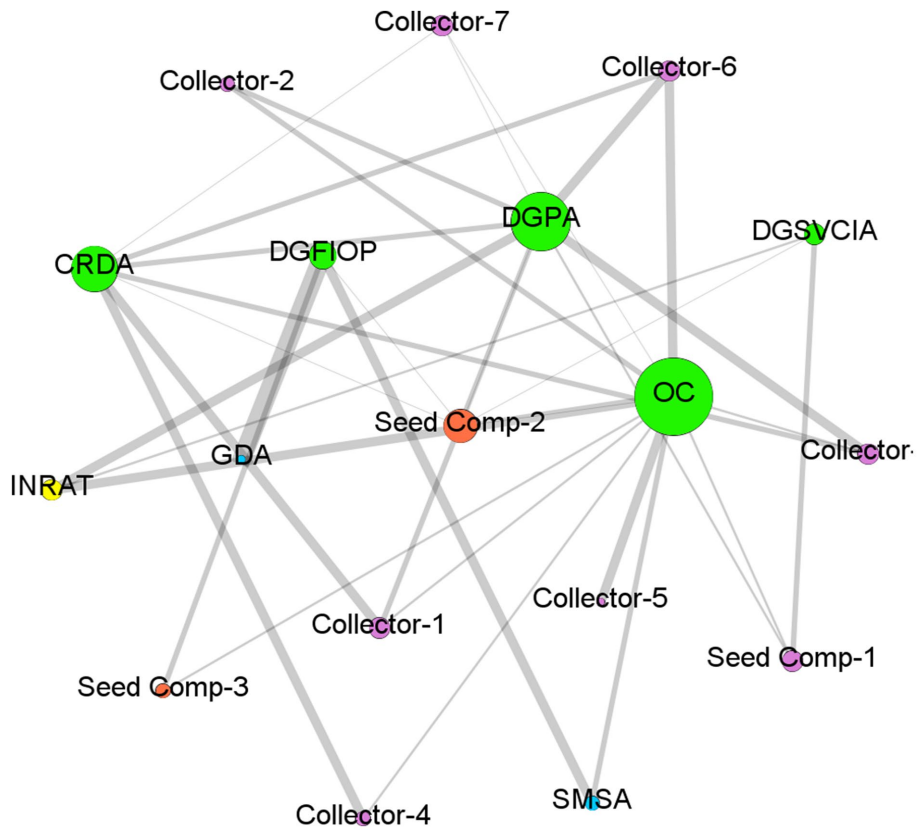


FIGURE 3

Network mapping of actors involved in the function "governance, strategic planning, and administration" (Node colors represent stakeholder categories: green = public institutions; purple = private actors (collectors-distributors, seed companies); orange = seed companies (formerly cooperatives); sky blue = professional organizations; yellow = research institutions). The thickness of the edges represents the frequency of interactions between actors, with thicker lines indicating more frequent or stronger exchanges.

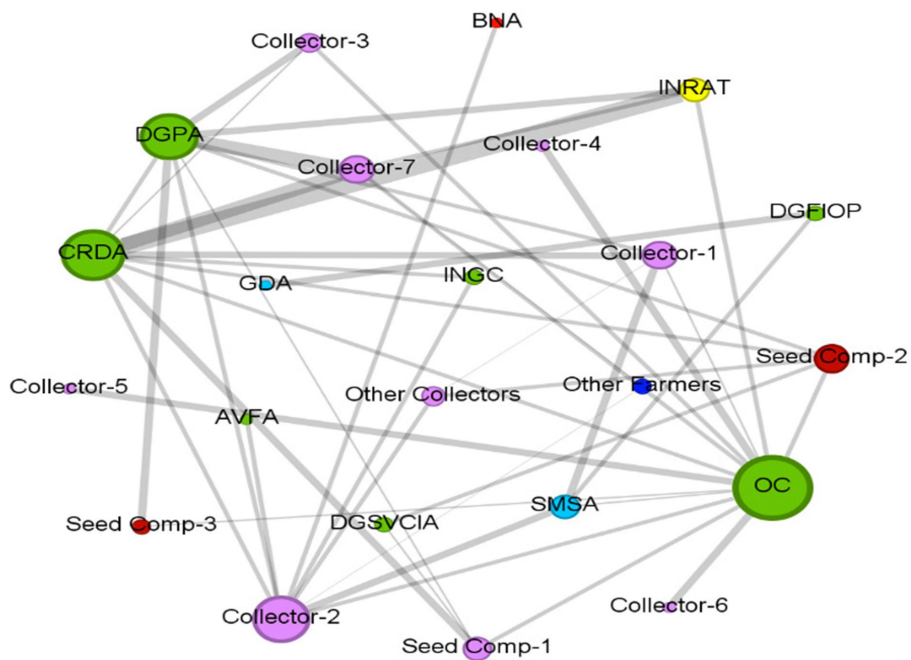


FIGURE 4

Network mapping of actors involved in the function "access to information and knowledge sharing" (Node colors represent stakeholder categories: green = public institutions; purple = private actors (collectors-distributors, seed companies); orange = seed companies (formerly cooperatives); sky blue = professional organizations; yellow = research institutions; blue = farmers; red = banks).

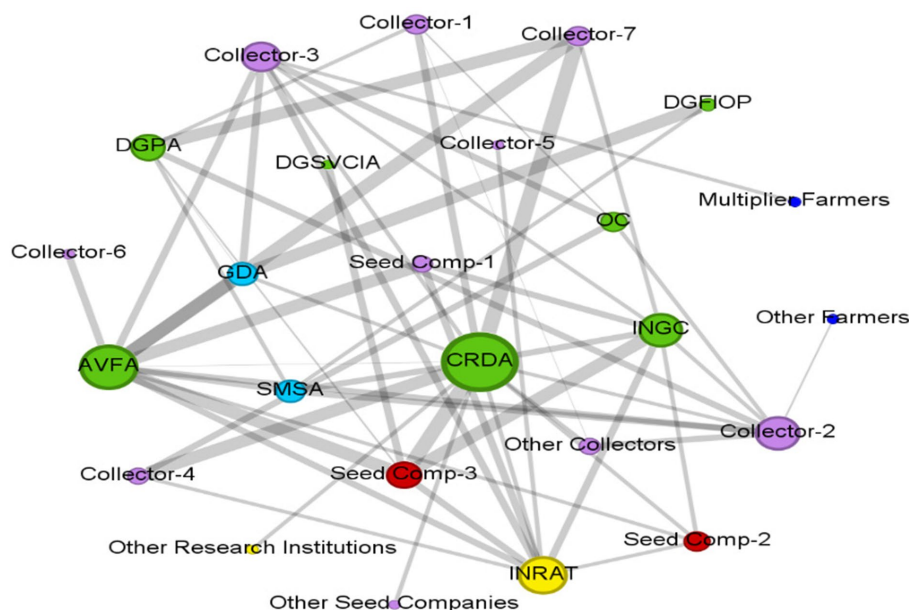


FIGURE 5

Network mapping of actors involved in the function "awareness and training" (node colors represent stakeholder categories: green = public institutions; purple = private actors (collectors–distributors, seed companies); orange = seed companies (formerly cooperatives); sky blue = professional organizations; yellow = research institutions; blue = farmers).

socio-economic conditions, these actors organize training sessions and awareness campaigns tailored to local needs. The AVFA disseminates agricultural practices, enhancing farmers' knowledge through training, technical information, and awareness campaigns in coordination with collectors-distributors, INRAT, and CRDA. A national cereal extension program, implemented with INGC, targets farm-saved wheat seeds, which account for roughly 80% of total wheat seed use, improving quality toward certified standards and strengthening seed security. Working closely with the CRDA, AVFA, and INGC, the INRAT promotes the adoption of new varieties through field trials and demonstration plots, allowing farmers to observe innovations firsthand. Although its direct reach to farmers is mediated by intermediaries, INRAT exerts strategic influence by providing technical knowledge adapted to local socio-economic and regional contexts.

Collectors-distributors demonstrate moderate integration within the WSS network. Large-scale collectors interact with 7 actors (weighted degree of 69) and the medium-scale collectors with 8 actors (weighted degree of 72), both with similar closeness centrality scores of 0.583. Many are also farmers or represent farmer groups, collaborating closely with the AVFA. Their field-level connections enable them to act as strategic intermediaries, channeling agricultural practices and innovations to farmers, with influence shaped by local context and network position.

Seed companies provide technical guidance on improved varieties and cultivation techniques and organize training sessions with CRDA, AVFA, INGC, and INRAT, supporting knowledge dissemination and fostering innovation within the WSS. Local-level actors, such as SMSAs and GDAs, maintain direct links with farming communities, primarily through CRDA, AVFA and collectors-distributors. With moderate closeness centrality (0.432) and weighted degrees of 50 (SMSAs) and 68 (GDAs), they are not central but act strategically as information relays. Their peripheral positions highlight untapped potential to support extension services and facilitate two-way

communication between farmers and institutional actors, particularly in community-based contexts.

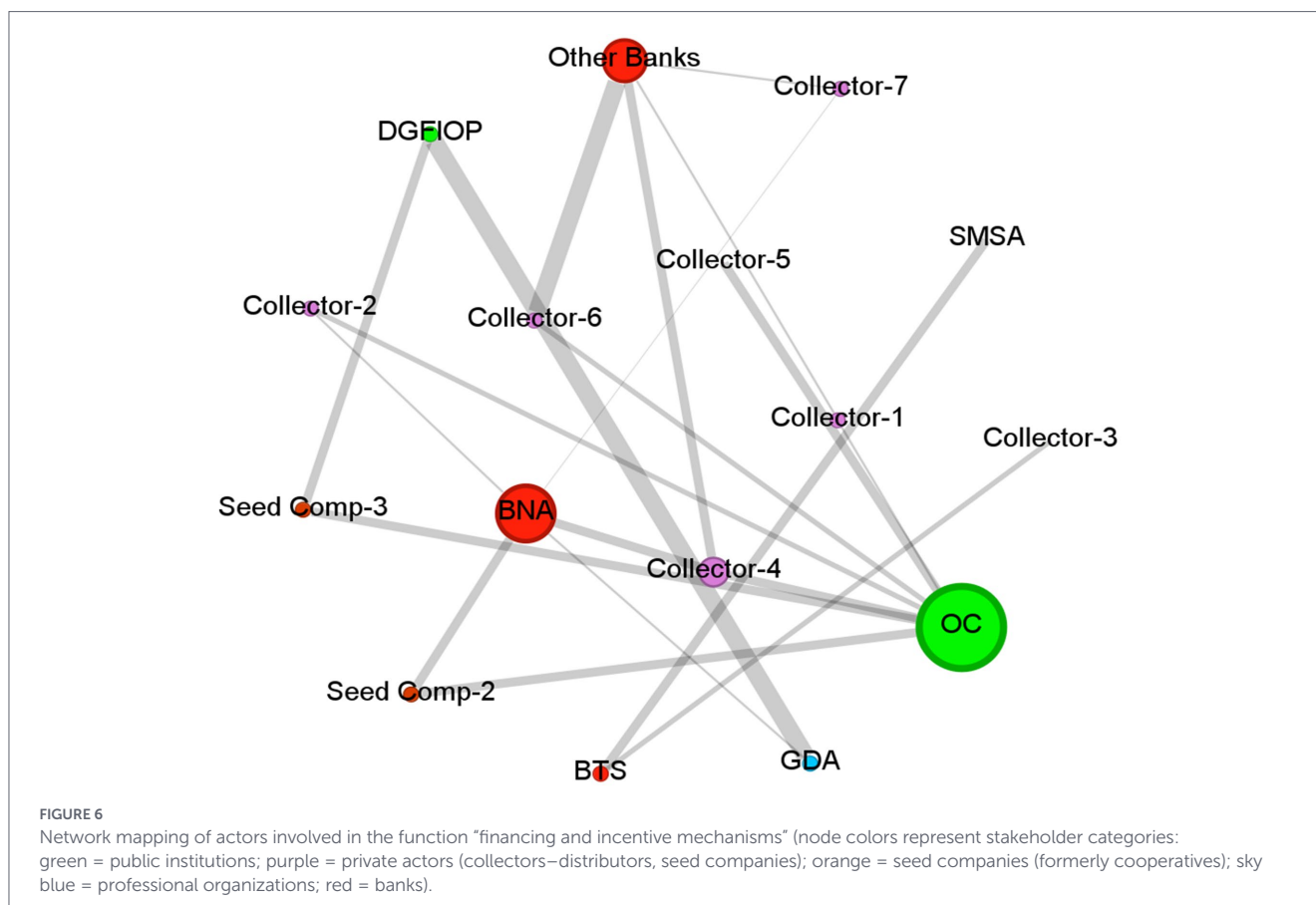
These results demonstrate that strategic influence in the WSS emerges from functional roles and interactions, not just network centrality, with moderately connected actors serving as critical leverage points for knowledge transfer, coordination, and adoption of certified wheat seeds.

### 3.4 Financing and incentive mechanisms

Results of the financing function (Table 3; Figure 6) indicate that the OC, National Agricultural Bank (BNA), and other banking institutions, including microfinance organizations, have the highest collaboration frequencies, interacting with 7, 5, and 4 actors, respectively. Their weighted degrees, 65 for the OC, 31 for BNA, and 36 for other banks, reflect the intensity and diversity of financial interactions within the WSS. Collectors-distributors (large-scale) collaborate with 3 actors, with a weighted degree of 36, indicating moderate financial integration through ties with major banks. Closeness centrality highlights their positions, with the OC at 1, BNA at 0.723, and other banks and collectors-distributors ranging between 0.613 and 0.610.

These findings indicate that OC and BNA occupy strategic positions in the financing network, playing central roles in facilitating and coordinating financial flows across actors. The Ministry of Agriculture promotes certified wheat seeds adoption by providing subsidies covering about 30% of production costs. These subsidies are managed by OC through a dedicated public fund within the annual State budget, highlighting how central actors leverage financial mechanisms to influence adoption and resource allocation across the WSS.

Collectors-distributors must demonstrate financial capacity, for example through certified checks, to ensure sound management and efficient stock control, mainly through interactions with OC, BNA and other banks. The subsidy system, however, constitutes a major



bottleneck. Its complexity and administrative requirements, managed by the OC, can create a financial lag, as investments in breeder seeds are made before subsidy disbursement, affecting farmers' cash flow and operational efficiency.

The BNA plays a key role by providing short-term loans to cover farmers' operational needs and input procurement for production, processing, packaging, and marketing. Other institutions, such as the Tunisian Solidarity Bank (BTS), offer preferential-rate loans to support seed and inputs purchase, financing cereal campaigns and contributing to sector sustainability.

Collectors-distributors provide supplier credit to farmers, enabling purchases wheat seeds, fertilizers, equipment, and other inputs. Operating under OC's supervision, they play a pivotal role in ensuring timely and efficient production. In contrast, the DGFIO, despite its formal mandate in agricultural financing, occupies a peripheral position in the WSS network, with low closeness centrality (0.202) and a moderate weighted degree (36). Its limited involvement reflects a focus on strategic and administrative functions, focused on policy design and fund, while operational responsibilities are delegated to OC and banking institutions. This highlights how formal authority does not always translate into operational influence, with network integration and functional engagement shaping actors' impact on financial flows.

### 3.5 Production and commercialization

In the production and commercialization function, seed companies are key structuring actors. Large-scale companies have maximum closeness centrality (1.000), a weighted degree of 117, and eigenvector centrality

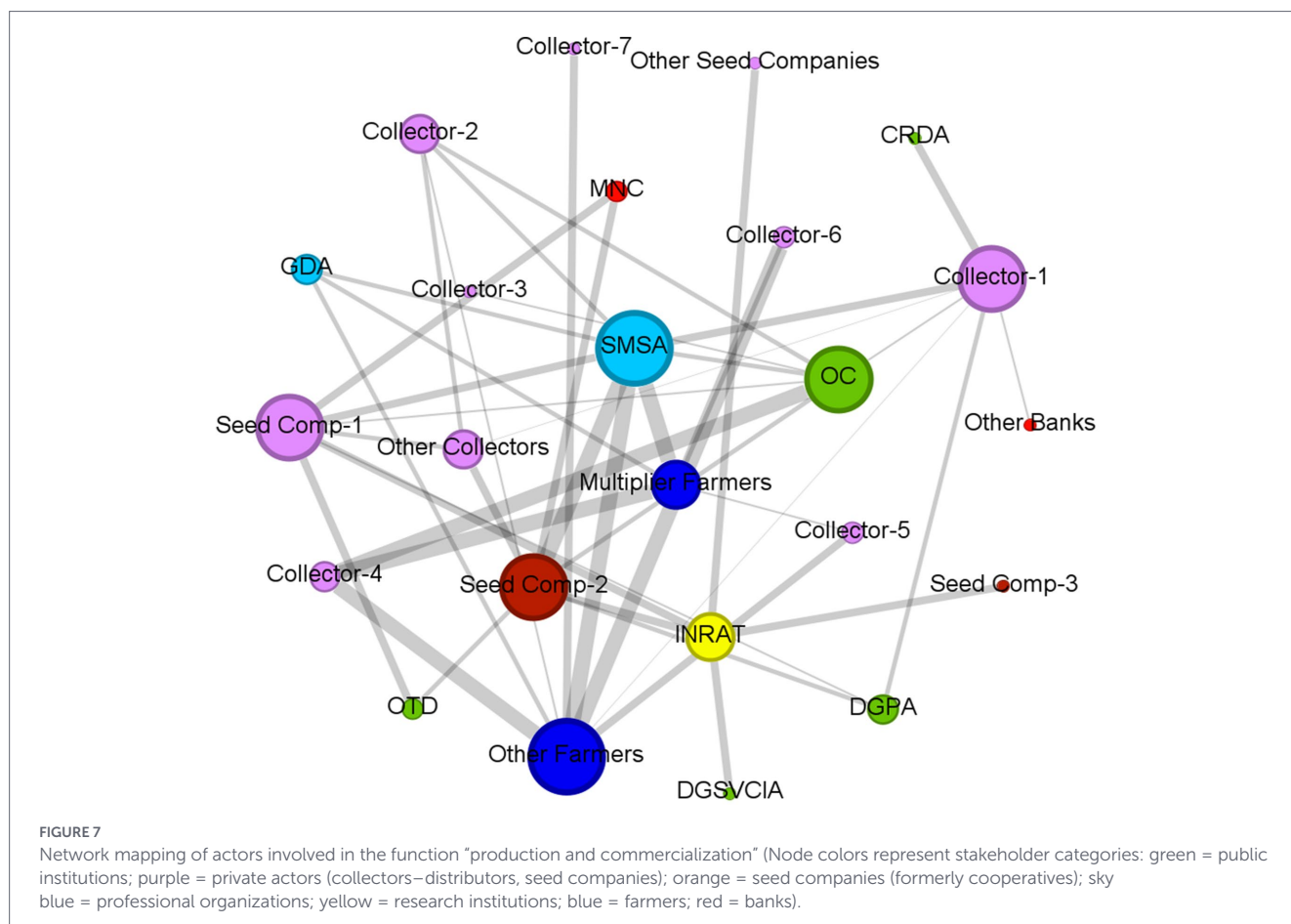
of 0.560, reflecting their pivotal role in coordinating seed flows. Smaller, localized companies show a weighted degree of 54, with high closeness (0.829) and significant eigenvector centrality (0.522) (Table 3; Figure 7).

Producers (other farmers) and multiplier farmers occupy complementary positions within the production and commercialization network. Producers have a high weighted degree (81), moderate closeness centrality (0.530), and eigenvector centrality of 0.442, indicating strong integration into distribution channels. Multiplier farmers with a weighted degree of 61, higher closeness centrality (0.594), and eigenvector centrality of 0.479, act as intermediaries between seed companies and final users. They play a critical role in seed production, controlled wheat seed multiplication, ensuring compliance with quality standards.

The OC plays a central role in the production and commercialization network, interacting with 7 actors and showing a high weighted degree of 107. Its closeness centrality of 0.725 indicates a strategic position as an information hub and coordinator. As a key actor, the OC facilitates wheat seed circulation, implementations quality policies, and connects collectors-distributors with seed companies, thus structuring and securing certified seeds production and distribution.

Collectors-distributors have weighted degree ranging from 24 to 39 and closeness centrality between 0.59 and 0.73, reflecting substantial interactions and good network integration. Their position enables them to coordinate effectively between producers and the OC, ensuring smooth circulation of certified seeds and supporting the implementation of quality standards across the network.

Certified wheat seed production is carried out through contractual arrangements between seed companies and multipliers. The process follows a rigorous certification procedure, with systematic quality controls



during production and commercialization. Production volumes are determined by orders from collectors-distributors. Seed companies report variety-specific data to the OC, which allocates quantities based on estimated farmer demand at the governorate level. As the monopoly holder, the OC supervises cereal purchasing and commercialization, organizes storage through collectors-distributors, and oversees national marketing. Collectors-distributors ensure the timely seed availability at their centers while maintaining direct commercial links with farmers.

INRAT occupies a relatively peripheral position in the production and marketing network, with 5 interactions, a weighted degree of 60, and low closeness centrality (0.325), reflecting its upstream role in varietal research and breeder seed production rather than direct commercial flows. Nevertheless, INRAT remains structurally important by developing high-performing varieties. These varieties are licensed to seed companies under commercial agreements, reinforcing INRAT's central scientific contribution to the WSS and its indirect influence on network efficiency.

Functional SNA reveals that the network's efficiency hinges not only on the structural centrality of seed companies but also critically on the operational roles of multiplier farmers and collectors-distributors, which ensure coordination, quality compliance, and timely seed distribution across the system.

## 4 Discussion

Building on insights from the Social Network Analysis, this section explores pathways to strengthen Tunisia's WSS by enhancing governance structures, optimizing actor interactions, and addressing

coordination bottlenecks. These measures aim to increase the adoption of certified cereal seeds to at least 30% while contributing national food sovereignty and system autonomy by ensuring farmers' access to high-quality, locally adapted seeds and enhancing the system's resilience under socio-economic and climatic constraints.

### 4.1 Strengthening governance and key actors

The governance of Tunisia's WSS combines central and territorial actors, whose interactions determine coordination, decision-making, and information flows. At the central level, the OC and the DGPA occupy strategic positions by regulating, planning, and financing wheat seed-related activities.

However, this concentration of authority entails risks of dependency and administrative rigidity, which can slow decision-making and disproportionately burden smallholders (Mulesa et al., 2021; Monticone et al., 2024). Strengthening the autonomy, resources, and decision-making capacities of other actors is therefore critical for achieving more balanced and resilient governance.

Territorial actors, particularly the CRDA and collectors-distributors, serve as essential intermediaries between central authorities to farmers. Their functional positions complement those of central actors by facilitating local coordination, supporting decision-making, and ensuring timely seed distribution. Enhancing their capacities through training, digitalization, and gradual, balanced, and coordinated decentralization would enable them to serve as effective conduits of innovation and system resilience, improving information flows, adoption of

certified seeds, and overall network efficiency (Akpo et al., 2020; Westengen et al., 2023; De Boef et al., 2025).

Formalized partnerships between central and territorial actors, including the DGPA, OC, CRDA, INGC, INRAT, and seed companies, could institutionalize shared responsibilities, enhance transparent governance, and provide mutual incentives. By promoting participatory decision-making and reducing coordination bottlenecks, such frameworks would foster trust among actors, encourage private sector investment in varietal research, and strengthen the production and distribution of certified seeds (Aseete et al., 2023; Mishra et al., 2025).

Inclusive governance platforms, integrating public institutions, private companies and farmer organizations can further improve coordination, system resilience, and investment in WSS (Shilomboleni et al., 2023). By reducing institutional bottlenecks and promoting participatory decision-making, such platforms trust among actors and support efficient production, distribution, and adoption of certified seeds (Westengen et al., 2023).

Strengthening local organizational structures, through the formalization of small and medium-sized collectors into larger cooperatives or well-structured associations, enable their active participation in governance bodies and strategic seed commissions. This formalization strengthens the overall efficiency of the system, facilitates broader adoption of certified seeds, and reinforces the resilience of the WSS (Sisay et al., 2017; Jaleta et al., 2023).

## 4.2 Digitalization and information flow

Enhancing the digital capacities of intermediary actors, such as the OC, the CRDA and collectors- distributors, is crucial for improving information flow within the WSS. Integrated digital platform providing real-time, geo-referenced data accessible via mobile devices can support timely and well-informed decision-making (Bolfe et al., 2020). Coupled with training and feedback channels that allow farmers to report field observations, these tools enable adaptive adjustments to production and distribution strategies. Such measures reduce information asymmetries, strengthen coordination, and promote broader adoption of certified wheat varieties (Manevska-Tasevska et al., 2021; Adamsons-Fiskovica and Grivins, 2022).

Digital and participatory approaches demonstrate the potential of combining technology with adaptive governance to improve information flows in seed systems. Such mechanisms, including mobile platforms, e-learning tools, and real-time databases, can enhance coordination among sector actors, facilitate timely decision-making, and provide tailored guidance to farmers (Balogun et al., 2022; Abate et al., 2023). By overcoming geographical and informational barriers, these tools support continuous learning, improve the adoption of innovations, and strengthen the responsiveness and efficiency of the wheat seed system in Tunisia (Abate et al., 2023).

Integrating digitalization with participatory and adaptive governance can substantially improve information flow, enhance system responsiveness, and support broader adoption of certified seeds in Tunisia. Implementing digital tools that enable real-time stock and demand management, prioritize regional needs, ensure transparent exchanges among actors, and provide traceability of seed value chain can strengthen decision-making, reduce mismatches between supply and demand, and foster trust and accountability throughout the wheat seed system.

## 4.3 Extension and farmer engagement

The collaboration between public institutions (AVFA, CRDA, INGC, INRAT) and private actors (seed companies,

collectors–distributors) establishes a continuous technical support system for farmers. Formalizing these partnerships through clear framework agreements and shared objectives combined with systematic monitoring and evaluation, can enhance coordination, track impact, and support the continuous improvement of the WSS (Rattunde et al., 2021; Joshi and Braun, 2022).

Integrating experienced seed multiplier farmers into extension activities leverages their local knowledge and credibility, facilitating the adoption of improved wheat varieties and agronomic practices. Through demonstrations, experimental plots, and innovation platforms, these farmers provide practical tools for locally validating new varieties and techniques, fostering co-construction and context-specific adaptation. Their dual role as both seed producers and extension intermediaries positions them as pivotal actors in bridging research outputs with on-farm practices, thereby strengthening system effectiveness (Steinke et al., 2022; Gharbi et al., 2025).

Lead farmers, recognized for their technical expertise and community credibility, further extend the reach of extension programs. By reporting farmers' observations and needs, they ensure that extension content remains relevant and actionable, while also facilitating local adaptation of innovations. Acting as both practitioners and communicators, lead farmers play a pivotal role in linking research with adoption, enhancing the overall impact and sustainability of extension efforts (Van Campenhout et al., 2017; Antwi-Agyei and Stringer, 2021).

## 4.4 Financing and investment mechanisms

Financing constitutes a key structural factor for the effective functioning of the WSS. Seasonal loans from the BNA facilitate farmers' access to inputs, equipment, and operational resources, while the OC manages subsidies, reimbursing farmers for part of certified seed costs and overseeing national seed allocation. Alternative mechanisms, such as supplier credit from collectors–distributors, exist but remain constrained by their economic capacity. Strengthening financial resilience therefore requires improved coordination among banks, public institutions, and seed system actors, potentially through structured public–private partnerships. Tailored instruments, including microcredits, credit guarantees for seed producers, and agricultural insurance covering climatic and phytosanitary risks, could enhance sector stability and ensure timely access to essential resources (Kayongo and Mathiassen, 2023; Otieno et al., 2023). Collectors–distributors should operate under clear contractual frameworks, with robust monitoring and traceability mechanisms to mitigate financial risks.

Simplifying Tunisia's current subsidy system could further support investment in certified seed production. Reducing administrative complexity, implementing advance or staggered disbursements, and improving transparency would improve cash flow for farmers, reduce bottlenecks, and incentivize greater participation in seed production (Opie et al., 2022; Alawode, 2025).

Collaboration between public and private financial institutions, including guarantee funds and preferential-rate credits, as well as cooperative banks and specialized credit schemes, can improve access to finance for seed producers and multipliers, supporting the expansion of certified seed production. These insights suggest that combining tailored financial instruments with enhanced institutional coordination can boost resilience and promote sustainable investment within the WSS (Rafik et al., 2021; Yigezu et al., 2021; Gemechu et al., 2024).

## 5 Conclusion

The SNA of Tunisia's wheat seed system highlights both its strengths and vulnerabilities. Centralized governance, dominated by the OC and DGPA, ensures coherence and responsiveness at the national scale, yet it constrains flexibility, limits the involvement of local and regional actors, and increases administrative burdens. This configuration risks undermining adaptability, resilience and equity, particularly for smallholders, who are the most affected by the rigid procedures.

Unlocking the system's potential requires greater recognition of the needs of local actors, such as the CRDA, collectors-distributors, and SMSA entities, whose proximity to farmers allows them to play a decisive role in dissemination, support, and adoption. Enhancing digital platforms, implementing feedback mechanisms (thus enhancing the information flows about seeds), and promoting participatory governance can reduce information asymmetries, strengthen coordination, and foster adaptive responses to climatic and market uncertainties. Simultaneously, diversifying financial instruments, including microcredits, insurance schemes, and structured public-private partnerships, would secure investments and sustain the multiplication and distribution of certified seeds. By linking these levers, local actor engagement, digitalization, and financial mechanisms, the system can operate as an integrated, resilient network.

A systemic transformation of the WSS through decentralization, transparency, and institutional innovation, is needed beyond technical reforms. Such a transition would not only reinforce certified seed adoption but also strengthen the overall resilience of the agricultural sector, offering transferable lessons for other North African seed systems undergoing agroecological transitions.

Although SNA approach provides crucial insights about the functional structure and actor's interactions within the WSS, certain methodological limitations should be considered. First, power asymmetries among actors are not fully captured by network metrics, as centrality measures reflect structural positions but may not reveal informal authority or hierarchical dynamics. Second, the analysis relies on interview data, which may be influenced by informant bias, including strategic responses in the context of centralized governance. Third, the network represents a static snapshot of interactions at the time of data collection, limiting the ability to capture temporal dynamics, evolving collaborations, or changes resulting from policy interventions. Nevertheless, the use of multiple data sources and the analysis of several functional networks enhance the robustness of the findings, allowing SNA to reliably identify key structural dependencies and coordination bottlenecks.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and

institutional requirements. Verbal informed consent was obtained from all participants prior to the interviews.

## Author contributions

IG: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. HO: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. MD: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. WT: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. NF: Data curation, Writing – original draft. MO: Investigation, Supervision, Writing – original draft. HB: Supervision, Writing – review & editing. AF: Writing – review & editing. MA: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Validation, Funding acquisition, Supervision, Project administration.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

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