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Developing SIBIMA: A Digital Innovation Infrastructure for Collaborative Hybrid Maize Breeding and Community-Based Seed Systems

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ABSTRACT: The increasing complexity of collaborative hybrid maize breeding and community-based seed production systems has created substantial challenges related to information management, communication, transparency, knowledge exchange, licensing administration, and institutional coordination. Conventional coordination mechanisms frequently become inadequate when innovation processes involve multiple actors operating across geographically dispersed locations and diverse institutional environments. This study aimed to develop the Seed Information System for Community-Based Seed Management (SIBIMA) as a digital innovation infrastructure designed to strengthen collaborative breeding and community-based seed systems. A qualitative case study approach combined with a design-oriented research perspective was employed to examine the experiences of CorresCo and its collaborative network. Data were collected through direct observation, semi-structured interviews, focus group discussions, and document analysis. Data analysis involved data reduction, categorization, triangulation, and thematic analysis to identify recurring patterns associated with collaboration, knowledge exchange, institutional development, and digital transformation. The findings indicate that increasing levels of collaboration simultaneously increase the complexity of coordination processes, thereby creating challenges associated with information exchange, traceability, transparency, and collective decision-making. In response to these challenges, SIBIMA was developed as an integrated framework encompassing breeding management, production management, knowledge management, and institutional management. The proposed framework functions not merely as an information management system but as a digital innovation infrastructure that supports communication, collective learning, licensing administration, and community empowerment. This study contributes to the advancement of agricultural innovation system theory by integrating technological, organizational, and institutional dimensions within a community-based seed system while offering a practical framework for strengthening seed sovereignty and promoting sustainable agricultural development.

1. INTRODUCTION

Seed systems are crucial for enhancing agricultural productivity and ensuring food security, especially in developing nations where the availability of quality seeds is inconsistent. In various scenarios, seed systems comprise a mix of formal entities, such as research institutions and seed enterprises, alongside informal or community-oriented networks that support local seed production and distribution. While formal systems are often associated with standardized quality control and large-scale dissemination, they frequently face limitations in reaching smallholder farmers and adapting to local agroecological conditions (Louwaars & de Boef, 2012; McGuire & Sperling, 2016; Sperling et al., 2020).

In hybrid maize systems, the intricacies of seed production are considerably greater than those found in open-pollinated varieties. The creation of hybrid cultivars necessitates the ongoing generation of novel combinations of genetically diverse inbred lines, which are then subjected to thorough evaluation via multi-site yield trials and stability analyses. These processes involve multiple actors, including plant breeders, seed producers, regulatory bodies, and market actors, all of whom must operate in a coordinated manner (Duvick, 2005; Hallauer et al., 2010). In numerous contexts within developing countries, the collaboration among these stakeholders continues to be inadequate, leading to inefficiencies in the management of parental lines, hybrid development, and the distribution of seeds. As a result, key components within seed systems often operate in a fragmented manner, leading to inefficiencies and limited innovation outcomes (Spielman et al., 2009; Louwaars & de Boef, 2012).

Recent viewpoints regarding the Agricultural Innovation System highlight that agricultural innovation is influenced not only by technological progress but also by the efficiency of interactions between the various stakeholders within the system. In this framework, innovation emerges through networks that facilitate knowledge exchange, resource sharing, and coordinated action (Hall et al., 2005; Klerkx et al., 2012). Despite this acknowledgment, the function of digital platforms in facilitating coordination within intricate seed systems—especially those that incorporate collaborative breeding processes—has yet to be thoroughly examined. This perspective has subsequently evolved toward the concept of knowledge communities, emphasizing that innovation is generated through continuous interactions among institutions, organizations, and individuals involved in collective learning processes. Consequently, agricultural innovation systems should be understood not only as technological environments but also as dynamic social and institutional arrangements that facilitate knowledge creation, adaptation, and dissemination (Touzard et al., 2015).

At the same time, there is growing interest in community-based approaches to seed system development, where farmers, local seed enterprises, and researchers collaboratively engage in seed production and dissemination. While such systems have shown potential in improving access to seeds and enhancing local capacity (Sperling et al., 2020; Almekinders et al., 2019), they often lack structured mechanisms for coordinating information flows, managing breeding materials, and aligning production activities across actors. Furthermore, long-term collaboration requires transparent governance structures, equitable benefit-sharing mechanisms, and clearly defined institutional arrangements capable of maintaining trust and commitment among participating actors (Liang et al., 2022). This gap becomes more critical in hybrid maize systems, where the synchronization of breeding, parental seed multiplication, and hybrid seed production is essential.

Similar challenges have been observed in various contexts, including participatory breeding programs and decentralized seed systems, where limited coordination among actors constrains the scaling of innovation (Ceccarelli & Grando, 2007; Dawson et al., 2011; McGuire & Sperling, 2016). While these approaches have successfully enhanced farmer participation and local adaptation, they often lack systemic integration across breeding, seed production, and market distribution functions.

To address these challenges, this study introduces SIBIMA (Seed Information System for Community-Based Seed Management) as a digital coordination platform designed to support a community-based hybrid maize seed system in Indonesia. Unlike conventional agricultural information systems, SIBIMA is conceptualized not only as a data management tool but as a coordination infrastructure that integrates breeding, seed production, and distribution processes within a unified framework.

More specifically, SIBIMA enables the formation of a Collaborative Hybrid Breeding Network, in which multiple breeders can exchange inbred lines, design hybrid combinations, and collectively generate new hybrid varieties. Through this mechanism, the platform facilitates the sharing of genetic resources and supports coordinated hybrid generation processes, thereby expanding the diversity of hybrid combinations and accelerating breeding outcomes. In this context, the Collaborative Hybrid Breeding Network functions as an intermediary mechanism that connects individual innovation activities with the broader agricultural innovation system. Through this arrangement, knowledge, genetic resources, and technological capabilities are continuously exchanged among participating actors, thereby strengthening collective learning and institutional adaptation processes (Touzard et al., 2015). In addition, the system supports the coordination of parental seed multiplication, hybrid seed production, and the monitoring of seed flows within the community-based seed network. This approach aligns with emerging views that digital platforms act as coordination infrastructures in complex innovation systems (Klerkx et al., 2019; Eastwood et al., 2017).

By embedding these functions within a digital platform, SIBIMA provides a structured mechanism for linking knowledge generation, production processes, and market interactions. This integration allows the system to operate as a coordination backbone within the broader seed system, connecting breeders, farmer seed producers, local seed enterprises, and other stakeholders.

This study aims to develop and describe the conceptual design and functional architecture of SIBIMA as a digital coordination platform within a community-based hybrid maize seed system. In contrast, this study proposes an integrated model that embeds collaborative hybrid breeding within a structured agricultural innovation system, supported by a digital coordination platform. Furthermore, the study examines how the platform supports the formation of a Collaborative Hybrid Breeding Network and contributes to the strengthening of coordination within the agricultural innovation system. The findings are expected to contribute to the literature on digital agriculture and seed systems by providing a novel framework for integrating collaborative breeding and community-based seed production. Unlike previous studies that primarily focused on either breeding technologies or community-based seed production, the present study integrates technological, organizational, and institutional dimensions within a single conceptual framework. By positioning SIBIMA as a digital innovation infrastructure, this study extends existing perspectives on agricultural innovation systems and provides an alternative model for strengthening collaborative hybrid breeding and community-based seed systems.

Despite significant progress in domestic maize production, the Indonesian hybrid maize seed sector remains highly dependent on transnational seed corporations. Although hybrid seeds are produced within the country, control over breeding technologies, germplasm resources, intellectual property rights, production systems, and distribution channels remains concentrated among a relatively small number of actors. As a result, local farmers, researchers, and national seed enterprises continue to face substantial barriers in accessing critical resources required to participate actively in the seed innovation process (Spielman & Kennedy, 2016; Louwaars & Boef, 2012; FAO, 2023). This condition demonstrates that strengthening domestic seed production capacity alone is insufficient to achieve seed sovereignty. Sustainable seed systems also require broader access to genetic resources, technological capabilities, knowledge networks, intellectual property management, and equitable market participation. Consequently, strengthening coordination among researchers, local seed enterprises, farmer groups, and governmental institutions becomes an essential component of sustainable agricultural development (McGuire & Sperling, 2016; FAO, 2023).

This situation highlights an important distinction between seed independence and seed sovereignty. Seed independence refers primarily to the ability of a country to produce sufficient quantities of seed domestically, thereby reducing dependence on imports. Seed sovereignty, in contrast, encompasses a broader and more comprehensive perspective. It refers to the collective capacity of a nation and its communities to control the generation, management, distribution, exchange, and utilization of genetic resources, technologies, and knowledge associated with seed systems (Kloppenburg, 2014; La Via Campesina, 2017; IPES-Food, 2022).

The concentration of control within multinational corporations has generated several structural challenges. These include limited access to parental lines, reduced genetic diversity, unequal distribution of economic benefits, dependence on externally controlled technologies, and the marginalization of local innovation capacities. Furthermore, highly centralized breeding systems often exhibit limited responsiveness to local agroecological conditions and the specific needs of smallholder farmers (Pingali, 2012; McGuire & Sperling, 2016; World Bank, 2022).

Community-based approaches have increasingly been recognized as promising alternatives for strengthening agricultural innovation systems. Previous studies have demonstrated the importance of local institutions, social networks, collective action, and participatory approaches in improving the sustainability and resilience of agricultural production systems (Pretty, 2018; Klerkx et al., 2019; FAO, 2021). However, the implementation of such approaches in hybrid maize seed systems remains limited because of the complex technical requirements associated with hybrid breeding, parental seed multiplication, quality control, certification procedures, and large-scale distribution.

The present study argues that technological innovation alone is insufficient to establish a resilient and sovereign seed system. Contemporary innovation studies increasingly recognize that innovation emerges through continuous interaction among multiple actors operating within interconnected social, institutional, and technological networks (Klerkx et al., 2010; Leeuwis & Aarts, 2011). Sustainable transformation therefore requires the integration of collaborative plant breeding, social capital, local

institutional development, intellectual property protection, farmer empowerment, and digital coordination mechanisms. (Leeuwis & Aarts, 2018; Klerkx et al., 2020; OECD, 2023). Consequently, this study extends the Agricultural Innovation System (AIS) perspective by proposing a Community-Based Hybrid Maize Seed Innovation System (CBHMSIS) that integrates these components into a coherent and coordinated framework. Although digital agriculture has developed rapidly during the last decade, most existing platforms have focused primarily on farm management, market information, traceability, and supply chain management (Klerkx et al., 2019; Eastwood et al., 2017). Comparatively little attention has been devoted to the integration of hybrid breeding activities, community-based seed production, germplasm management, intellectual property protection, and collaborative innovation within a unified digital environment. This study addresses this gap through the development of SIBIMA as a digital coordination infrastructure within a Community-Based Hybrid Maize Seed Innovation System (CBHMSIS).

Within this framework, SIBIMA (Seed Information System for Community-Based Seed Management) functions not merely as an information management tool but as a digital coordination infrastructure that facilitates interactions among breeders, farmer seed producers, local seed enterprises, researchers, policymakers, and market actors. Through this mechanism, SIBIMA supports germplasm exchange, hybrid development, parental seed multiplication, intellectual property management, seed production planning, knowledge sharing, and the equitable distribution of benefits among stakeholders (FAO, 2022; World Bank, 2023; OECD, 2023).

Unlike conventional approaches that emphasize isolated technological interventions, the proposed model conceptualizes innovation as a collective and dynamic process embedded within social relationships, institutional arrangements, and collaborative networks. Following Leeuwis and Aarts (2011), communication is regarded not merely as a mechanism for transferring information but as an intermediary process that facilitates negotiation, learning, trust building, and institutional change among actors involved in innovation systems. Within this perspective, SIBIMA serves as an enabling infrastructure that supports communication, knowledge exchange, and collective action among breeders, researchers, seed enterprises, policymakers, and farming communities. By strengthening coordination among actors and integrating knowledge generation with practical implementation, the system seeks to improve innovation capacity while simultaneously contributing to the broader objective of national seed sovereignty.

Accordingly, this study aims to develop and describe a conceptual framework for integrating collaborative hybrid breeding, social capital, community-based seed production, and digital coordination mechanisms within an agricultural innovation system. Particular attention is given to the role of SIBIMA as an enabling platform that strengthens institutional linkages, promotes transparency, facilitates collective learning, and supports the long-term sustainability of community-based hybrid maize seed systems.

Agricultural innovation is increasingly understood as the outcome of continuous interactions among institutions, organizations, networks, and individuals operating within a particular innovation environment. Consequently, innovation should be viewed not merely as a technological outcome but also as a social and institutional process involving knowledge exchange, collective learning, and adaptive interactions among multiple stakeholders (Touzard et al., 2015). Unlike conventional linear approaches, which assume that knowledge flows unidirectionally from researchers to end users, the Agricultural Innovation System (AIS) perspective emphasizes continuous interaction, collective learning, and institutional adaptation among diverse stakeholders.

Within this perspective, innovation is understood not merely as the generation of new technologies but as the outcome of coordinated interactions among researchers, farmers, governmental agencies, seed enterprises, universities, financial institutions, extension organizations, and other supporting institutions. Consequently, the success of an innovation system depends not only on technological capability but also on the effectiveness of communication, institutional arrangements, knowledge exchange, and collaborative networks among actors.

Several studies have demonstrated that agricultural innovation systems play a fundamental role in improving agricultural productivity, strengthening institutional resilience, and accelerating technological adoption. Klerkx et al. (2012) argued that agricultural innovation should be viewed as a systemic process in which technological, organizational, economic, and social components interact continuously. Similarly, Hall et al. (2005) emphasized that innovation emerges from interactions among multiple actors rather than from isolated research activities. Contemporary innovation systems extend beyond national boundaries and increasingly incorporate regional, sectoral, technological, and network perspectives. Within this context,

innovation emerges from dynamic interactions among universities, industries, governments, and other stakeholders, reflecting the principles of the triple-helix model (Touzard et al., 2015).

Recent developments in agricultural innovation studies have further highlighted the importance of communication, social learning, and innovation brokerage in facilitating collective action among stakeholders. Leeuwis and Aarts (2011) proposed that communication should not be regarded merely as a mechanism for transferring information but rather as an intermediary process that supports negotiation, trust building, institutional change, knowledge exchange, and collective learning.

The present study adopts the AIS perspective because hybrid maize breeding represents a highly complex system involving multiple interconnected activities, including germplasm management, inbred line development, hybrid evaluation, seed multiplication, quality assurance, intellectual property protection, market development, and farmer empowerment. These activities require intensive coordination among actors possessing different capacities, resources, and institutional roles.

In Indonesia, the hybrid maize seed sector remains largely dominated by large national and multinational corporations that possess substantial technological capabilities, financial resources, and distribution networks. Although these corporations have contributed significantly to increasing the availability of hybrid maize seed, their dominance has simultaneously generated structural challenges, including limited access to parental lines, unequal distribution of benefits, restricted participation of local actors, and a growing dependence on externally controlled technologies.

Recent advances in digital agriculture have transformed the structure of agricultural innovation systems by strengthening connectivity, accelerating information exchange, and improving coordination among geographically dispersed actors. Consequently, digital technologies increasingly function as innovation infrastructures that facilitate communication, collective learning, and adaptive governance processes within agricultural systems (Klerkx et al., 2019).

The development of hybrid maize varieties is a complex and resource-intensive process that extends beyond conventional plant breeding activities. In addition to the development of inbred lines and hybrid combinations, hybrid maize breeding requires coordinated activities involving germplasm management, combining ability evaluation, multi-location testing, parental seed multiplication, quality control, certification, commercialization, and market development. Consequently, the success of breeding programs depends not only on technological capability but also on the effectiveness of institutional coordination and collaborative relationships among participating actors (CIMMYT, 2019).

In conventional seed systems, breeding activities are generally concentrated within large public institutions or multinational corporations that possess extensive research infrastructure, financial resources, and distribution networks. Although these institutions have contributed significantly to technological advancement and increased seed availability, centralized systems often create structural limitations, including restricted access to genetic resources, unequal distribution of benefits, limited participation of local actors, and growing dependence on externally controlled technologies (Louwaars & de Boef, 2012; Spielman & Kennedy, 2016). Such conditions may weaken local innovation capacity and reduce the adaptability of breeding programs to specific agroecological conditions.

To address these limitations, this study proposes a Collaborative Hybrid Breeding Network (CHBN) as an institutional mechanism designed to strengthen interactions among researchers, universities, local seed enterprises, farming communities, governmental agencies, and supporting organizations. Within this framework, each actor performs a specific role according to its knowledge, experience, resources, and institutional capacity. Researchers contribute scientific knowledge and breeding expertise, farming communities provide practical experience and field-based knowledge, seed enterprises facilitate production and commercialization activities, and governmental institutions support regulatory and institutional processes (Biggs, 1990; Leeuwis & Aarts, 2011). Collaborative breeding networks enable geographically dispersed researchers, breeders, seed producers, and supporting institutions to combine complementary resources, expertise, and technologies within a shared innovation environment. Such collaborative arrangements facilitate collective learning processes, strengthen institutional adaptation, and accelerate the generation and dissemination of innovations among participating actors (Touzard et al., 2015).

Unlike conventional approaches, the proposed model emphasizes collective learning, transparency, reciprocity, and equitable benefit-sharing among participating actors. Collaboration is therefore understood not merely as a technical arrangement but as a dynamic process through which trust, knowledge, and innovation capacities are continuously developed and strengthened (Pretty, 2003; Ostrom, 1990).

The collaborative framework encompasses a series of interconnected activities, including germplasm exchange, inbred line development, hybrid formation, multi-location evaluation, variety registration, licensing mechanisms, parental seed production, commercial seed multiplication, and market expansion. This process allows innovation to emerge through continuous interactions among actors rather than through isolated institutional activities (Fischer et al., 2015). Collaborative-based hybrid breeding networks also facilitate the exchange of germplasm resources, strengthen collaborative learning processes, and improve access to breeding technologies among participating actors. In addition, the involvement of local seed producers and farming communities contributes to strengthening institutional capacity, promoting knowledge dissemination, and supporting more equitable benefit-sharing mechanisms (Hendrayana et al., 2026).

An important component of the network is the establishment of transparent intellectual property protection mechanisms. Licensing agreements, plant breeders' rights, benefit-sharing arrangements, and royalty management systems encourage broader participation while ensuring that breeders, farmers, and seed enterprises receive equitable benefits from their contributions. This mechanism also promotes long-term sustainability by strengthening incentives for continuous innovation and collaborative research (UPOV, 1991; FAO, 2010). As collaborative networks expand, coordination mechanisms become increasingly important because participants often possess different objectives, capabilities, and institutional responsibilities. Consequently, transparent governance structures, clearly defined intellectual property arrangements, and equitable benefit-sharing mechanisms become essential prerequisites for maintaining long-term collaboration (Liang et al., 2022).

Accordingly, the CHBN framework serves as an essential component of the Community-Based Hybrid Maize Seed Innovation System (CBHMSIS). By integrating technological innovation, social capital, institutional development, and community empowerment, the proposed framework seeks to establish a more inclusive, resilient, and sustainable hybrid maize seed system that contributes to the broader objective of national seed sovereignty (World Bank, 2007; FAO, 2011).

The increasing complexity of modern seed systems has significantly expanded the need for effective communication, information exchange, coordination, and collaborative decision-making among stakeholders. In hybrid maize breeding systems, interactions occur continuously among researchers, breeders, farmers, seed enterprises, governmental institutions, and other supporting organizations. Digital platforms enable multiple actors to exchange information, coordinate activities, and collectively generate new knowledge within a shared innovation environment. Consequently, the effectiveness of digital technologies depends not only on technological capabilities but also on institutional arrangements and the quality of social interactions among participating actors (Touzard et al., 2015). Consequently, the effectiveness of innovation processes depends not only on technological advancement but also on the efficiency of communication networks and institutional coordination mechanisms (Hall et al., 2005; Klerkx et al., 2012).

Conventional information management systems are generally characterized by fragmented data structures, limited interoperability, insufficient transparency, and restricted accessibility among participating actors. These limitations frequently result in inefficiencies in germplasm management, breeding coordination, seed production planning, variety evaluation, licensing administration, and knowledge dissemination processes (Louwaars & de Boef, 2012; McGuire & Sperling, 2016).

Recent developments in digital agriculture have encouraged the adoption of information technologies to support agricultural innovation processes. Digital platforms have evolved beyond their original role as data repositories and are increasingly recognized as infrastructures that facilitate communication, collective learning, institutional interaction, and collaborative decision-making among actors operating within agricultural innovation systems (Eastwood et al., 2017; Klerkx et al., 2019).

From this perspective, digital technologies should not be regarded merely as instruments for transferring information. Instead, they should be understood as enabling mechanisms that facilitate negotiation, coordination, trust formation, and social learning among multiple actors involved in innovation networks (Leeuwis & Aarts, 2011). Consequently, digital platforms play a strategic role in strengthening social capital and supporting the sustainability of collaborative innovation systems.

Despite considerable advances in digital agriculture, relatively few studies have focused on the integration of collaborative breeding activities, community-based seed production, germplasm management, intellectual property protection, royalty administration, and knowledge-sharing mechanisms within a unified digital environment (Klerkx et al., 2019; McGuire & Sperling, 2016). The implementation of digital technologies in agricultural systems is frequently constrained by differences in technological capabilities, institutional capacity, organizational culture, and access to information resources. Consequently, successful digital transformation requires continuous adaptation, institutional learning, and effective governance mechanisms

(Velten et al., 2021). This gap becomes increasingly important in community-based seed systems, where effective coordination among geographically dispersed actors constitutes a fundamental prerequisite for long-term sustainability.

Accordingly, this study proposes the integration of a digital coordination platform as a fundamental component of the Community-Based Hybrid Maize Seed Innovation System (CBHMSIS). Within this framework, digital technologies function not merely as management tools but as institutional infrastructures that facilitate interaction, collaboration, transparency, accountability, and collective action among all actors participating in the innovation process.

SIBIMA (Seed Information System for Community-Based Seed Management) was developed as a digital coordination platform designed to support interactions among researchers, plant breeders, seed producers, governmental institutions, universities, and farming communities involved in community-based hybrid maize breeding systems. Unlike conventional information systems, which primarily function as repositories for data storage and retrieval, SIBIMA was designed as an integrated infrastructure that facilitates communication, coordination, transparency, and collaborative decision-making among participating actors.

The development of SIBIMA was motivated by the increasing complexity of hybrid maize breeding activities, which require the continuous exchange of information across multiple stages of the innovation process. These activities include germplasm management, inbred line development, crossing programs, pedigree documentation, multi-location evaluation, parental seed multiplication, commercial seed production, licensing administration, royalty management, and knowledge dissemination. In conventional systems, these activities are often performed independently, resulting in fragmented information flows, inefficient coordination, and limited transparency among stakeholders.

Within the proposed framework, SIBIMA functions as an intermediary platform connecting actors within the Community-Based Hybrid Maize Seed Innovation System (CBHMSIS). Consistent with the Agricultural Innovation System perspective, the platform facilitates collective learning, institutional adaptation, and collaborative innovation processes among researchers, breeders, seed producers, governmental institutions, universities, and farming communities (Hall et al., 2005; Klerkx et al., 2012). Furthermore, communication is conceptualized not merely as the transfer of information but also as a mechanism for negotiation, trust building, coordination, and collective action among participating actors (Leeuwis & Aarts, 2011). From this perspective, SIBIMA serves as a digital innovation infrastructure that strengthens transparency, accountability, traceability, and knowledge exchange throughout the hybrid breeding process (Eastwood et al., 2017; Klerkx et al., 2019; Touzard et al., 2015; Liang et al., 2022).

From an operational perspective, SIBIMA consists of several interconnected components. The first component supports breeding management activities, including germplasm documentation, pedigree tracking, crossing design, combining ability evaluation, and multi-location testing. The second component focuses on production management by facilitating seed production planning, quality assurance procedures, inventory management, and distribution activities. The third component supports knowledge management through data sharing, documentation, communication, and collaborative learning activities. The fourth component focuses on institutional management by supporting licensing mechanisms, intellectual property protection, benefit-sharing arrangements, and royalty administration.

Consequently, SIBIMA is conceptualized not merely as a technological innovation but also as an institutional mechanism designed to strengthen collaboration, improve local innovation capacity, and support the long-term sustainability of community-based seed systems. Accordingly, SIBIMA is conceptualized not merely as a technological innovation but as an institutional mechanism designed to strengthen collaboration and support the long-term sustainability of community-based seed systems. Through this approach, the platform contributes to the broader objective of enhancing local innovation capacity while promoting national seed sovereignty.

2. MATERIALS AND METHODS

2.1 Research Design

This study was conducted within a community-based hybrid maize seed production system in Indonesia facilitated by CorresCo (Collaborative Research Company; PT CorresCo Seeds Indonesia). The system integrates plant breeding activities, seed production, licensing mechanisms, and local seed enterprises within a collaborative framework. As an emerging decentralized model, the system provides an opportunity to examine interactions among multiple actors involved in hybrid maize breeding and seed production activities.

The study employed a qualitative case study approach combined with a design-oriented research perspective to develop a digital coordination framework for community-based hybrid maize seed systems. The qualitative approach was selected because the study aimed to understand the interactions among multiple actors involved in collaborative breeding activities, community-based seed production, licensing arrangements, and knowledge exchange processes. Rather than testing predetermined hypotheses, the study focused on identifying coordination challenges and developing an institutional framework capable of addressing these challenges through digital innovation.

A case study approach was adopted because the phenomenon under investigation involved complex social, technological, and institutional interactions occurring within a specific organizational context. The collaborative framework facilitated by CorresCo provided an empirical setting for examining interactions among breeders, seed producers, universities, farmer groups, and governmental institutions involved in hybrid maize seed development. These interactions subsequently provided the empirical foundation for the development of SIBIMA.

In addition, a design-oriented perspective was incorporated because the study aimed not only to investigate existing conditions but also to develop a practical framework capable of strengthening coordination, communication, transparency, and decision-making processes among stakeholders. The resulting framework integrates technological innovation, institutional development, social learning, and community empowerment within a unified system (Hall et al., 2005; Leeuwis & Aarts, 2011; Klerkx et al., 2012).

2.2 Research Context

The study was conducted within the collaborative hybrid maize seed production network established by CorresCo (Collaborative Research Company; PT CorresCo Seeds Indonesia) in Indonesia. The network connects researchers, universities, local seed enterprises, farmer groups, governmental institutions, and other supporting organizations involved in hybrid maize breeding and seed production activities.

Unlike conventional seed production systems, the collaborative framework emphasizes decentralized production, collective learning, equitable benefit sharing, and community empowerment. Participating actors contribute according to their respective capacities while simultaneously obtaining access to technological knowledge, germplasm resources, production facilities, and market opportunities (Biggs, 1990).

The empirical context of this study encompassed germplasm exchange, inbred line development, hybrid formation, multi-location evaluation, parental seed multiplication, commercial seed production, licensing activities, royalty administration, training programs, and farmer assistance initiatives. As the collaborative network expanded, increasing levels of complexity generated challenges associated with information management, communication, transparency, traceability, and institutional coordination. To address these constraints, SIBIMA was conceptualized as a digital innovation infrastructure designed to strengthen interactions among participating actors while supporting transparency, collaborative learning, collective action, and long-term institutional sustainability (Leeuwis & Aarts, 2011; Klerkx et al., 2019).

2.3 Data Collection

Primary data were collected through direct observation, semi-structured interviews, and focus group discussions involving researchers, plant breeders, local seed producers, farmer groups, university partners, and other stakeholders participating in collaborative hybrid breeding activities. Data collection focused on breeding activities, seed production processes, licensing arrangements, institutional relationships, knowledge exchange mechanisms, and coordination processes within the collaborative network.

Semi-structured interviews and focus group discussions were conducted to obtain a comprehensive understanding of institutional relationships, collaborative decision-making processes, benefit-sharing mechanisms, and operational constraints encountered by participating actors. These activities also facilitated the identification of recurring patterns associated with institutional development, social learning, technological adaptation, and collaborative governance (Hall et al., 2005; Leeuwis & Aarts, 2011).

Secondary data were obtained from institutional reports, technical documents, operational records, licensing agreements, field notes, training materials, internal reports, scientific publications, and relevant policy documents related to agricultural

innovation systems, hybrid maize breeding, and digital agriculture. The combination of these data sources facilitated data triangulation and strengthened the credibility of the findings (Denzin & Lincoln, 2017).

2.4 Model Development Process

The development of the Seed Information System for Community-Based Seed Management (SIBIMA) followed an iterative process involving problem identification, stakeholder analysis, information flow mapping, model development, and continuous refinement. This process was intended to ensure that the resulting framework accurately reflected the operational, social, and institutional characteristics of the collaborative network.

The initial stage focused on identifying coordination challenges related to communication, transparency, traceability, licensing management, knowledge exchange, and collaborative decision-making processes. Simultaneously, stakeholder mapping was conducted to identify the roles, responsibilities, and interactions among breeders, researchers, seed producers, universities, farmer groups, governmental institutions, and supporting organizations participating in the network (Hall et al., 2005; Klerkx et al., 2010).

The subsequent stage involved mapping operational activities associated with hybrid maize breeding, including germplasm management, crossing programs, field evaluation, seed production, licensing arrangements, and royalty administration. Based on these findings, a conceptual framework was developed to integrate technological, social, and institutional dimensions within a unified digital environment (Louwaars & de Boef, 2012; Leeuwis & Aarts, 2011; Klerkx et al., 2019).

Finally, the proposed framework was continuously refined through stakeholder consultations, discussions, and practical implementation within the collaborative network. Feedback obtained during this process was incorporated into the final model to strengthen its adaptability, operational feasibility, and long-term sustainability. The overall development process of SIBIMA is presented in Figure 1.

2.5 Data Analysis

Data analysis was conducted using an interactive qualitative approach involving data reduction, data categorization, triangulation, thematic analysis, and interpretation. This approach facilitated the identification of relationships among technological, organizational, and institutional components within the collaborative hybrid maize seed production system (Denzin & Lincoln, 2017).

The initial stage involved data reduction and categorization, in which information obtained from observations, interviews, focus group discussions, and documentary sources was organized into several analytical categories, including collaborative breeding activities, community-based seed production, knowledge management, social capital, digital transformation, and institutional development (Hall et al., 2005; Leeuwis & Aarts, 2011).

Subsequently, triangulation and thematic analysis were performed to identify recurring patterns, institutional relationships, communication mechanisms, and coordination processes within the collaborative network. The themes emerging from this process served as the basis for the conceptualization and development of SIBIMA as a digital innovation infrastructure supporting collaborative hybrid maize breeding systems (Denzin & Lincoln, 2017; Klerkx et al., 2012; Eastwood et al., 2017).

3. RESULTS AND DISCUSSION

3.1 Evolution of Collaborative Hybrid Breeding at CorresCo

The collaborative hybrid maize breeding system at CorresCo emerged as a response to the limitations of conventional breeding systems, which are commonly characterized by centralized organizational structures and limited access to germplasm resources, technological knowledge, breeding facilities, and financial support (Biggs, 1990; Hall et al., 2005). In response to these limitations, CorresCo established a collaborative network involving researchers, universities, local seed producers, farming communities, governmental institutions, and other supporting organizations.

Initially, collaborative activities focused on germplasm evaluation, inbred line development, and hybrid formation. As the network expanded, additional activities were incorporated, including multi-location testing, parental seed production, commercial seed multiplication, farmer training, licensing arrangements, and royalty management. This expansion substantially

increased the complexity of information exchange, communication, decision-making, and institutional coordination processes within the network.

Along with the expansion of breeding activities, partnerships among participating actors evolved beyond conventional contractual arrangements and became mechanisms for collective learning, institutional development, and capacity building. Similar findings were reported by Hendrayana et al. (2026), who highlighted the importance of collaboration, knowledge sharing, community participation, and institutional support within community-based hybrid maize production systems.

The development of social capital through trust, reciprocity, collective learning, and knowledge exchange further strengthened interactions among participating actors (Hall et al., 2005; Klerkx et al., 2010; Leeuwis & Aarts, 2011). However, the growing complexity of these interactions increased the need for more effective coordination mechanisms, ultimately leading to the development of SIBIMA as an integrated digital coordination platform supporting collaborative hybrid breeding activities.

3.2 Development of the Community-Based Seed Production Network

The expansion of collaborative breeding activities gradually led to the establishment of a community-based seed production network involving multiple stakeholders operating at different stages of the seed value chain. The network was developed to improve the accessibility, affordability, and sustainability of hybrid maize seed production while simultaneously expanding opportunities for local participation in innovation processes.

Unlike conventional seed systems, the collaborative model implemented by CorresCo emphasizes decentralized production mechanisms and collaborative institutional arrangements. Researchers and breeders contribute technological knowledge and genetic resources, whereas local seed producers participate in seed multiplication, processing, quality assurance, packaging, and distribution activities.

As the network expanded, partnerships among participating actors evolved beyond conventional contractual arrangements and became mechanisms for collective learning, capacity development, and institutional strengthening. Hendrayana et al. (2026) reported similar findings, highlighting the importance of collaboration, knowledge sharing, community participation, and institutional support within community-based hybrid maize production systems. The sustainability of these collaborative arrangements depends not only on technological capabilities but also on equitable benefit-sharing mechanisms capable of maintaining trust, commitment, and institutional stability among participating actors (Liang et al., 2022).

The implementation of this collaborative model enabled participating actors to access improved technologies, strengthen technical capacities, and establish more sustainable economic relationships. Consequently, the network functioned not only as a production system but also as a mechanism for knowledge exchange, collective learning, and community empowerment (Biggs, 1990; Leeuwis & Aarts, 2011).

As the network continued to expand, increasing numbers of participants, geographical locations, breeding materials, seed production units, and institutional relationships generated considerable challenges related to communication, information management, traceability, transparency, and decision-making processes. Similar challenges have been reported in studies of integrated seed systems and community-based agricultural innovation networks (Louwaars & de Boef, 2012; McGuire & Sperling, 2016). These conditions ultimately provided the empirical foundation for the development of SIBIMA as a digital coordination platform.

3.3 Identification of Coordination Constraints

The expansion of collaborative breeding activities and community-based seed production networks substantially increased the complexity of interactions among participating actors. Although this collaborative approach generated significant benefits, the increasing number of stakeholders, activities, production sites, and institutional relationships simultaneously created considerable coordination challenges.

Field observations revealed that the principal constraints were related to fragmented information flows, limited traceability, delayed communication, inconsistent documentation practices, and the absence of an integrated coordination mechanism. These challenges became increasingly apparent as collaborative activities expanded from germplasm management and hybrid development to seed production, licensing administration, and royalty management (Louwaars & de Boef, 2012; McGuire & Sperling, 2016).

The expansion of collaborative networks also generated challenges related to trust, transparency, accountability, and equitable benefit-sharing mechanisms among participating actors. Hendrayana et al. (2026) emphasized that institutional adaptation, collective learning, and mutually beneficial partnerships are essential for maintaining the long-term sustainability of community-based hybrid maize production systems.

Similar findings have been reported in previous studies highlighting the importance of effective communication, clearly defined roles, and continuous knowledge exchange in collaborative agricultural systems (Velten et al., 2021; Liang et al., 2022).

The analysis further indicated bahwa many coordination problems were rooted in organizational and institutional factors rather than technological limitations alone. Unequal access to information, differences in institutional objectives, variations in technical capacity, and geographical dispersion frequently reduced the efficiency of collaborative activities (Kilelu et al., 2017; Meemken & Bellemare, 2020).

Within the CorresCo network, these constraints affected germplasm exchange, pedigree documentation, field evaluation, production planning, inventory management, licensing administration, and royalty distribution. Consequently, the increasing complexity of the network highlighted the need for a comprehensive coordination mechanism. In response to these challenges, SIBIMA was developed as a digital innovation infrastructure integrating technological, organizational, and institutional dimensions within a unified collaborative environment.

3.4 Development of SIBIMA

The development of the Seed Information System for Community-Based Seed Management (SIBIMA) was initiated in response to the increasing complexity of collaborative hybrid maize breeding activities and community-based seed production networks. The growing number of participants, breeding materials, production sites, institutional arrangements, and communication channels highlighted the limitations of conventional coordination mechanisms and emphasized the need for a more integrated approach.

The initial stage of development focused on identifying critical coordination points across the innovation process, including germplasm management, pedigree documentation, crossing design, field evaluation, seed production, licensing administration, royalty management, and knowledge dissemination. These activities generated large volumes of information that required systematic organization, continuous updating, and efficient communication among participating actors.

Experiences within the CorresCo network demonstrated that effective collaboration depends not only on technological capabilities but also on trust, reciprocity, transparency, collective learning, and adaptive institutional arrangements. Previous studies have similarly emphasized the importance of communication, knowledge exchange, clearly defined roles, equitable benefit-sharing mechanisms, and mutually beneficial partnerships in sustaining collaborative agricultural systems (Velten et al., 2021; Liang et al., 2022; Hendrayana et al., 2026).

Consequently, SIBIMA was designed as an integrated digital environment connecting researchers, breeders, local seed enterprises, universities, farmer groups, governmental institutions, and other stakeholders. Rather than functioning solely as an information repository, the platform was conceptualized as a digital innovation infrastructure supporting communication, coordination, collective learning, transparency, and collaborative decision-making (Leeuwis & Aarts, 2011; Eastwood et al., 2017; Klerkx et al., 2019).

The resulting framework integrates four principal components, namely breeding management, production management, knowledge management, and institutional management. Through the integration of these components, SIBIMA supports activities ranging from germplasm management and hybrid development to seed production, licensing administration, benefit-sharing arrangements, and institutional learning.

Figure 1 presents the conceptual framework of SIBIMA as a digital innovation infrastructure designed to strengthen collaboration, improve coordination, facilitate collective learning, and support community-based hybrid maize seed systems.

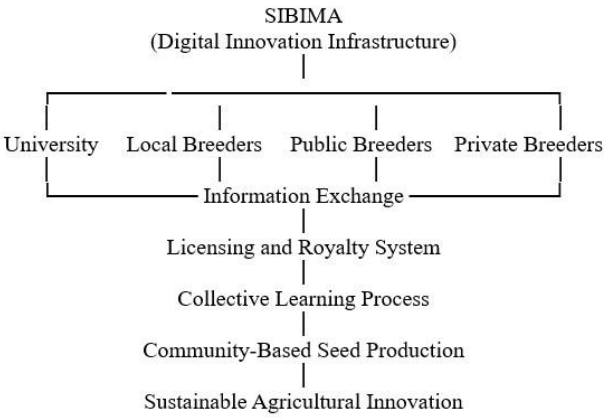

Figure 1. Conceptual framework of SIBIMA as a digital innovation infrastructure supporting collaborative hybrid maize breeding and community-based seed systems.

3.4 Development of SIBIMA

The development of the Seed Information System for Community-Based Seed Management (SIBIMA) represented an adaptive response to the increasing complexity of collaborative hybrid maize breeding and community-based seed production activities. As the CorresCo network expanded, the diversity of actors, institutions, production units, and communication channels also increased substantially. Consequently, conventional coordination mechanisms became insufficient to maintain transparency, traceability, accountability, and effective communication among participating actors.

The need for an integrated coordination mechanism became increasingly apparent as breeding activities expanded to include germplasm acquisition, inbred line development, hybrid formation, multi-location testing, parental seed multiplication, commercial seed production, licensing administration, royalty distribution, and capacity-building programs. These activities generated large volumes of information that required continuous monitoring, efficient communication, and effective coordination among participating actors (Louwaars & de Boef, 2012; McGuire & Sperling, 2016).

The initial development of SIBIMA focused on identifying the principal actors involved in the collaborative network and analyzing their interactions. Researchers and breeders contributed scientific knowledge and genetic resources, whereas local seed producers, farmer groups, universities, governmental institutions, and supporting organizations participated in seed production, training, commercialization, and institutional development activities. These interactions highlighted the need for a unified coordination mechanism capable of facilitating information exchange and collective decision-making (Hall et al., 2005; Klerkx et al., 2010).

The resulting framework integrates four principal dimensions: breeding management, production management, knowledge management, and institutional management. The breeding management component was developed to facilitate germplasm documentation, pedigree management, crossing programs, and field evaluations. Production management focused on seed multiplication, inventory management, quality assurance, and distribution processes. Knowledge management supported the documentation and dissemination of technical information, training materials, and institutional experiences. Institutional management was intended to strengthen transparency, licensing administration, royalty distribution, and collaborative governance mechanisms.

Experiences within the CorresCo network demonstrated that technological infrastructure alone is insufficient to ensure the sustainability of collaborative innovation systems. Effective collaboration depends upon trust, transparency, reciprocity, collective learning, and adaptive institutional arrangements among participating actors (Hendrayana et al., 2026; Velten et al., 2021; Kilelu et al., 2017).

Consequently, SIBIMA was conceptualized not merely as an information management system but as a digital innovation infrastructure designed to strengthen communication, coordination, knowledge exchange, institutional learning, and community empowerment.

3.5 SIBIMA as a Digital Innovation Infrastructure

The findings of this study indicate that SIBIMA extends beyond the conventional definition of an information management system. Rather than functioning solely as a digital repository, the platform serves as an integrated innovation infrastructure that facilitates communication, coordination, knowledge exchange, and collaborative decision-making among actors involved in hybrid maize breeding and community-based seed production activities.

This finding is consistent with the Agricultural Innovation System (AIS) perspective, which emphasizes that innovation emerges through interactions among multiple actors rather than through the isolated activities of individual organizations (Hall et al., 2005; Klerkx et al., 2012). From this perspective, digital technologies function not merely as technical tools but also as mechanisms that strengthen institutional relationships, collective learning, and collaborative innovation processes.

Evidence obtained from the CorresCo network demonstrated that effective collaboration depends upon the ability of participating actors to access information, exchange knowledge, coordinate activities, and establish mutually beneficial partnerships. These findings support previous studies emphasizing the importance of institutional learning and adaptive capacity in digitally enabled agricultural innovation systems (Eastwood et al., 2017; Klerkx et al., 2019).

The findings further indicate that technological innovation and institutional development are mutually reinforcing processes. Trust, reciprocity, transparency, collective learning, and adaptive governance mechanisms constitute essential foundations for sustaining long-term collaboration among participating actors (Hendrayana et al., 2026; Velten et al., 2021).

Within this context, SIBIMA performs five interconnected functions. First, the platform facilitates information management by integrating data generated throughout the breeding and seed production processes. Second, it strengthens communication and coordination among participating actors. Third, it promotes collective learning through the systematic documentation and dissemination of knowledge. Fourth, it supports licensing administration and benefit-sharing mechanisms. Finally, it contributes to strengthening institutional resilience by promoting transparency, accountability, and stakeholder participation.

Accordingly, SIBIMA may be conceptualized as a digital innovation infrastructure that integrates technological resources, institutional arrangements, social relationships, and knowledge management processes within a unified collaborative environment. This integrated approach strengthens the adaptive capacity of community-based seed systems while simultaneously supporting sustainable agricultural innovation.

3.6 Implications for Seed Sovereignty

The findings of this study indicate that the contribution of SIBIMA extends beyond improvements in operational efficiency within collaborative breeding programs. More broadly, the platform contributes to strengthening institutional capacity, facilitating collective learning, and supporting more inclusive and resilient community-based seed systems.

Seed sovereignty is generally understood as the capacity of farmers, breeders, local communities, and supporting institutions to maintain control over genetic resources, seed production systems, knowledge, and distribution mechanisms while preserving the sustainability and diversity of agricultural systems (Louwaars & de Boef, 2012; McGuire & Sperling, 2016). From this perspective, technological innovation constitutes only one component of a broader institutional and social transformation process.

Empirical observations within the CorresCo network demonstrate that collaborative breeding and community-based seed production systems create opportunities for broader participation among researchers, local seed enterprises, farmer groups, universities, and governmental institutions. Through these interactions, knowledge, technologies, and economic benefits can be distributed more equitably among participating actors. Similar findings were reported by Hendrayana et al. (2026), who emphasized the importance of institutional adaptation, social capital formation, collective learning, and equitable benefit-sharing mechanisms in strengthening the sustainability of collaborative agricultural systems.

The findings further indicate that technological infrastructure alone is insufficient to establish sustainable community-based seed systems. Trust, reciprocity, transparency, adaptive governance, and collective learning remain fundamental prerequisites for long-term collaboration (Hall et al., 2005; Klerkx et al., 2012; Velten et al., 2021).

Within this context, SIBIMA should not be interpreted as a prerequisite for achieving seed sovereignty. Instead, the platform should be understood as a supporting mechanism designed to facilitate communication, improve transparency, strengthen

institutional coordination, promote knowledge exchange, and enhance collective decision-making processes. Consequently, SIBIMA functions as an enabling infrastructure that strengthens the development of more resilient, inclusive, and sustainable community-based seed systems.

Accordingly, the framework proposed in this study offers an alternative approach to strengthening seed sovereignty by integrating technological innovation, collaborative governance, knowledge management, and community empowerment within a unified system. The experiences documented in this study suggest that digital innovation infrastructures can complement existing institutional arrangements while enhancing the adaptive capacity, resilience, and long-term sustainability of community-based seed systems.

3.7. Limitations and Future Research

This study focused on the conceptual development of the Seed Information System for Community-Based Seed Management (SIBIMA) based on empirical observations obtained from the CorresCo collaborative network. Consequently, the study did not include the development and evaluation of a fully operational digital platform.

In addition, the empirical context of this study was limited to collaborative hybrid maize breeding and community-based seed production systems in Indonesia. Therefore, the transferability of the proposed framework to other commodities, geographical regions, and institutional settings should be interpreted with caution.

Future studies may focus on the implementation and large-scale evaluation of the proposed framework to assess its effectiveness, adaptability, and long-term sustainability. Further research may also explore the integration of emerging technologies, including artificial intelligence, blockchain technology, geographic information systems (GIS), and decision-support systems, as well as comparative analyses involving different crops and agricultural innovation systems.

4. CONCLUSION

This study demonstrates that the increasing complexity of collaborative hybrid maize breeding and community-based seed production systems requires more integrated coordination mechanisms capable of accommodating technological, organizational, and institutional interactions among diverse stakeholders. Drawing upon empirical observations within the CorresCo network, the study identified several coordination challenges related to information management, communication, traceability, licensing administration, knowledge exchange, and collaborative decision-making processes.

These findings led to the development of the Seed Information System for Community-Based Seed Management (SIBIMA), which was conceptualized not merely as an information management tool but as a digital innovation infrastructure integrating breeding management, production management, knowledge management, and institutional management within a unified collaborative environment.

From a theoretical perspective, this study extends the Agricultural Innovation System (AIS) framework by integrating community-based hybrid breeding, collaborative governance, and digital innovation into a comprehensive conceptual model. The findings further demonstrate that technological innovation and institutional development are mutually reinforcing processes supported by trust, reciprocity, transparency, and collective learning.

From a practical perspective, the proposed framework contributes to strengthening the resilience, inclusiveness, and sustainability of community-based seed systems. However, SIBIMA should not be regarded as a prerequisite for achieving seed sovereignty. Instead, the platform functions as an enabling mechanism that supports communication, coordination, transparency, knowledge exchange, and collaborative decision-making among participating actors.

This study was conducted within the context of collaborative hybrid maize breeding activities in Indonesia. Therefore, further research is required to evaluate the applicability of the proposed framework across different commodities, geographical regions, and institutional environments, as well as to examine its implementation and long-term effectiveness under diverse operational conditions.

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AUTHOR CONTRIBUTIONS

Febri Hendrayana: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Project Administration, Writing—Original Draft, Writing—Review & Editing.

Iwan Setiawan: Supervision, Validation, Writing—Review & Editing.

Ahmad Choibar Tridakusumah: Supervision, Validation, Writing—Review & Editing.

Noladhi Wicaksana: Supervision, Validation, Writing—Review & Editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

This research was executed in alignment with established ethical standards pertinent to social and agricultural investigations. Data gathering was accomplished via field observations, semi-structured interviews, focus group discussions, and the evaluation of institutional documents associated with collaborative hybrid maize breeding and community-based seed production initiatives within the CorresCo network.

Participation in the interviews and discussions was entirely voluntary, with all participants apprised of the study's objectives prior to the commencement of data collection. Confidential information pertaining to breeding materials, licensing agreements, and commercial endeavors was handled with anonymity and utilized exclusively for research purposes.

The study did not encompass clinical interventions, experiments involving human subjects, nor animal experimentation that necessitated formal ethical approval.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Certain data are not publicly available because they contain confidential information related to breeding materials, licensing agreements, institutional partnerships, and commercial seed production activities within the CorresCo collaborative network.

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