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Article

COLLABORATIVE INNOVATION ECOSYSTEMS FOR DEFENSE SPACE TECHNOLOGY DEVELOPMENT: AN INTEGRATIVE LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

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Abstract: Defense-space capability depends on coordinating fragmented actors, knowledge, resources, and lifecycle processes across complex and security-sensitive technological environments. This study examines how collaborative innovation ecosystems enable the development, transfer, diffusion, operational adoption, and sustainment of defense-space technologies in support of sovereign capability. An integrative literature review synthesizes 63 peer-reviewed Scopus-indexed studies published between 2019 and 2025 across innovation ecosystems, Helix models, defense industry, aerospace engineering, technology transfer, and strategic autonomy. Quality appraisal classified 41 studies as high quality and 22 as moderate quality. The thematic synthesis identifies five interrelated mechanisms: ecosystem governance and orchestration; functional actor configuration; knowledge, resource, and absorptive-capacity integration; technology development and lifecycle capability; and defense-industrial transformation through transfer, diffusion, and self-reliance. Findings show that actor presence alone is insufficient; collaboration creates capability when it aligns priorities, institutionalizes roles, integrates knowledge and resources, and connects systems engineering with operational adoption and lifecycle learning. The study proposes an eight-layer framework culminating in sovereign defense-space capability and reconceptualizes self-reliance as progressive operational, maintenance, integration, production, innovation, and strategic autonomy rather than technological autarky.
Keywords: collaborative innovation ecosystem; defense-space technology; technology transfer; absorptive capacity; lifecycle capability; strategic autonomy

1. Introduction

Space systems are no longer peripheral instruments used only for scientific exploration or civilian communication. They have become part of the infrastructure through which states observe their strategic environment, communicate securely, navigate, collect intelligence, coordinate military operations, and maintain situational awareness. The growing military relevance of dual-use technologies has further blurred the boundary between civilian and defense space activities. Japan's experience, for example, demonstrates how civilian technological capabilities can gradually be adapted to support national security objectives in outer space . At the operational level, modern aerospace and satellite systems also depend on tightly integrated hardware, software, sensors, data-processing facilities, ground infrastructure, and maintenance systems. Their effectiveness is therefore determined not only by whether a platform can be developed or acquired, but also by whether it can be operated, maintained, upgraded, and integrated into a wider mission architecture throughout its lifecycle .

These characteristics make defense-space technology fundamentally different from conventional commercial products. Its development involves high financial costs, long technological cycles, security restrictions, uncertain demand, complex certification requirements, and limited access to critical components and knowledge. The sector is also shaped by geopolitical considerations because international partnerships may simultaneously provide access to advanced technology and create new forms of dependency. Defense cooperation can accelerate modernization through procurement, joint production, and technology transfer, but reliance on external suppliers may constrain operational readiness when supply chains, licenses, technical assistance, or political relations are disrupted. Studies of defense cooperation consequently emphasize the need to combine external partnerships with sustained investment in domestic technological and industrial capabilities . Similarly, research on strategic defense companies shows that national ambitions often remain disconnected from the organizational, technological, and supply-chain capabilities available within the domestic defense industrial base . However, no single organization can independently provide all the knowledge, capital, infrastructure, regulatory authority, operational experience, and industrial capacity needed to overcome these constraints. Universities and research institutions may generate scientific knowledge, but they do not necessarily possess the capacity to transform that knowledge into operational systems. Industrial firms can manufacture and integrate technologies, but their investment decisions depend on predictable demand, financing, regulation, and access to skilled personnel. Governments can define priorities and allocate resources, while military users provide operational requirements and feedback; nevertheless, these actors often work under different institutional incentives and time horizons. Defense-space technology development should therefore be understood as an ecosystem-level process rather than as a sequence of isolated research, procurement, or industrial activities.

The innovation ecosystem perspective provides a useful basis for this interpretation. It treats innovation as the result of interdependent relationships among organizations, institutions, resources, and knowledge flows. , in their study of China's artificial-intelligence ecosystem, show that technological development is shaped by interactions among government, industry, and academic or research institutions, as well as by the movement of skills, knowledge, funding, talent, and capital. The value of an ecosystem approach lies in its ability to explain these relationships rather than simply catalog the organizations involved. Emerging technologies require governance arrangements capable of managing economic, technological, institutional, and social interdependence across public and private actors (Arenal et al., 2020). similarly argue that innovation ecosystems must be examined as systems of feedback, resource flows, structural drivers, and policy levers. Their analysis highlights the importance of coordination across universities, firms, government bodies, financial institutions, and other organizations that exchange knowledge, skills, and ideas.

The Triple Helix model has long provided the dominant conceptual framework for studying such interaction through the relationship among universities, industry, and government. Its main contribution is the recognition that innovation emerges when institutional boundaries become more flexible and actors assume overlapping roles in knowledge production, commercialization, and public policy. However, the literature has gradually moved toward Quadruple, Quintuple, and other extended Helix models. This evolution reflects both theoretical developments and differences in the maturity of innovation systems. More technologically advanced ecosystems increasingly incorporate wider societal and institutional relationships, while less mature systems often remain focused on establishing basic university–industry–government linkages. further demonstrate that public actors, social concerns, and risk governance may need to be incorporated without abandoning the dynamic relationships at the core of the original Triple Helix model.

The expansion of Helix models nevertheless creates an analytical problem. Adding more actors does not necessarily produce a more effective ecosystem. A framework that merely lists government, universities, industry, users, financial institutions, media, or civil society may describe participation without explaining how collaboration affects technological outcomes. The more important questions concern role complementarity, coordination, trust, resource sharing, conflict resolution, and the conversion of relationships into collective capabilities. illustrate this distinction by showing that universities can serve as integrators and mediators in multistakeholder innovation rather than functioning solely as sources of research. Their findings suggest that ecosystem performance depends on active engagement and integration among stakeholders. Research on open innovation reaches a similar conclusion:

knowledge must cross organizational boundaries, but firms and institutions also require the capacity to recognize, absorb, and use that knowledge .

This issue is particularly important in defense-space technology, where collaboration operates under conditions of secrecy, export controls, intellectual-property restrictions, technological complexity, and asymmetric bargaining power. Evidence from the Portuguese defense industry indicates that open innovation and Helix-based collaboration can support the development, production, and testing of military products, but only when theoretical collaboration is translated into practical institutional and industrial arrangements . Dynamic capabilities are equally important because defense firms must be able to identify technological change, mobilize resources, reorganize competencies, and align company-level capabilities with national strategy . Thus, collaboration should not be treated as an outcome in itself. Its value lies in whether it produces shared infrastructure, skilled personnel, integrated knowledge, systems-engineering competence, and the capacity to manage technological change.

Technology transfer provides another example of why institutional interaction alone is insufficient. Transfer may involve equipment, technical documentation, licenses, manufacturing methods, training, joint ventures, or access to research facilities. Yet receiving technology does not ensure that the recipient can understand, reproduce, adapt, or improve it. describes university–industry collaboration as an exchange of knowledge, skills, resources, and capabilities, supported by intermediary organizations such as technology-transfer offices, research centers, incubators, and science parks. The effectiveness of these linkages depends on trust, communication, shared objectives, institutional support, and absorptive capacity. Where these conditions are weak, technology may be transferred contractually without being embedded in domestic organizations. Therefore, a further conceptual distinction must be made between technology development, technology transfer, diffusion, and operational adoption. Development concerns the creation, adaptation, testing, and maturation of technology. Transfer concerns the movement of knowledge or technological assets between organizations. Diffusion refers to the wider spread and use of technology, while operational adoption requires its integration into organizational routines, training, doctrine, infrastructure, maintenance, and mission systems. University–industry collaboration can generate patents, licenses, spin-offs, new products, and production capabilities, but its impacts vary according to institutional context and the mechanisms through which knowledge is used . In safety-critical aerospace systems, successful development also requires requirements definition, architecture design, validation, verification, and lifecycle support rather than a one-time act of technological acquisition .

Despite these insights, the relevant literature remains fragmented. Innovation ecosystem and Helix studies explain relationships among institutional actors but often give limited attention to the technical path from research to operational capability. Defense-industry studies examine procurement, industrial performance, technology dependence, and national strategy, but do not always explain how knowledge is integrated across the broader ecosystem. Aerospace engineering research provides detailed accounts of systems integration, verification, maintenance, and lifecycle management, yet usually treats institutional collaboration as external to the technical process. Technology-transfer studies explain knowledge exchange but frequently stop before diffusion, operational adoption, and long-term technological upgrading. As a result, there is still no integrated explanation of how a collaborative ecosystem transforms dispersed actors and resources into sovereign defense-space capability. Thus, this article addresses the following overarching research question: how do collaborative innovation ecosystems enable the development, transfer, diffusion, operational adoption, and lifecycle sustainment of defense-space technologies in support of sovereign defense-space capability? This article addresses this question through an integrative review of 63 Scopus-indexed studies covering collaborative innovation, Helix models, defense industry, space and aerospace technology, technology transfer, diffusion, lifecycle capability, and strategic autonomy. It examines how institutional actors, governance arrangements, knowledge flows, resources, and technological capabilities interact across the defense-space innovation process. Rather than treating collaboration, technology development, and strategic autonomy as separate phenomena, the review integrates them into a single analytical pathway extending from ecosystem formation to operational and lifecycle capability.

This article makes three contributions. First, it brings together bodies of literature that have largely developed in parallel, connecting innovation ecosystems and Helix models with defense-industrial and aerospace capability research. Second, it shifts attention from the presence of actors to the mechanisms through which actors align their objectives, integrate knowledge and resources, and build technological capacity. Third, it proposes an integrated framework linking institutional enablers, multi-actor collaboration, knowledge and resource integration, technology development, technology transfer and diffusion, operational adoption, lifecycle capability, and sovereign defense-space capability. In doing so, the article conceptualizes defense self-reliance not as technological autarky, but as the progressive ability to operate, maintain, integrate, adapt, and further develop critical defense-space systems.

2. Research Methodology

2.1 Review Design

This study employed an integrative literature review to examine how collaborative innovation ecosystems contribute to the development and sustainment of defense-space technologies. This approach was selected because the relevant literature is distributed across several fields, including innovation studies, defense-industry research, space and aerospace engineering, technology transfer, public policy, and strategic autonomy. An integrative review enables empirical, conceptual, policy-oriented, and technical studies to be examined within a common analytical structure, rather than limiting the synthesis to a single research design or discipline . The purpose of the review was not to claim exhaustive coverage of all publications related to defense-space innovation. Instead, it sought to develop a theoretically coherent explanation from a bounded and quality-appraised body of literature. This orientation is consistent with integrative reviews that aim to reconcile fragmented perspectives, identify relationships among concepts, and develop new conceptual frameworks from existing knowledge .

2.2 Analytical Corpus and Selection Logic

The analytical corpus consisted of 63 peer-reviewed, Scopus-indexed studies selected for their substantive relevance to the central research question. The studies represented different geographical contexts, research methods, theoretical traditions, and technological domains. They were retained when they provided an identifiable empirical, conceptual, policy, or technical mechanism related to at least one element of the defense-space innovation process. The selection logic focused on eight substantive areas:

1. multi-actor collaboration and innovation governance;
2. knowledge and resource integration;
3. strategic technology development;
4. technology transfer and absorptive capacity;
5. technology diffusion and organizational adoption;
6. aerospace or space-system lifecycle capability;
7. civil–military or dual-use technology integration; and
8. defense self-reliance or strategic autonomy.

Studies were not retained merely because they used terms such as *Helix*, *innovation*, *defense*, or *space*. Each article had to offer an extractable mechanism that could contribute directly or indirectly to explaining defense-space capability development. Sector-specific studies were used only when their findings could reasonably be transferred to complex technology ecosystems. Studies confined to tourism, marketing, small-business promotion, corporate social responsibility, or narrowly defined technical algorithms without an ecosystem or capability-building mechanism were not included in the analytical corpus. To manage the disciplinary diversity of the corpus, the 63 studies were classified into four evidence categories, as follows:

Table 1. Evidence Categories of Studies

Evidence category	Number of studies
Core defense and space evidence	20
Theoretical and transferable evidence	28
Technical mechanism evidence	12
Contextual enabling evidence	3
Total	**63**

The core evidence category included studies directly addressing defense industries, military-technological innovation, space security, dual-use systems, and defense self-reliance. The theoretical and transferable evidence category covered innovation ecosystems, Triple and extended Helix models, university–industry relations, open innovation, and collaborative governance. The technical mechanism evidence category provided insights into systems engineering, technology readiness, digital twins, aerospace maintenance, verification, integration, and lifecycle management. The contextual enabling evidence category addressed wider institutional, political, financial, and strategic conditions affecting technological capability.

2.3 Quality Appraisal

A design-sensitive quality appraisal was conducted to account for the methodological heterogeneity of the studies. A single appraisal standard based exclusively on quantitative or qualitative research would have been unsuitable because the corpus included case studies, surveys, conceptual articles, literature reviews, policy analyses, engineering frameworks, simulations, and technical demonstrations. Each article was assessed across seven domains, as follows:

1. clarity of the research aim;
2. appropriateness of the research design;
3. transparency of the data or source base;
4. analytical rigor;
5. evidentiary support for the findings;
6. acknowledgement of limitations or reflexivity; and
7. relevance to the purpose of the review.

Each domain was scored from 0 to 2, producing a maximum score of 14. Studies scoring 11–14 were classified as high quality, those scoring 8–10 as moderate quality, and those scoring 0–7 as low quality. The final corpus contained 41 high-quality studies and 22 moderate-quality studies, with no study classified as low quality. Moderate-quality studies were not automatically excluded. Instead, their findings were interpreted with greater attention to design limitations, contextual specificity, and the strength of the supporting evidence. Journal quartile was recorded as bibliographic information but was not treated as a substitute for methodological quality.

2.4 Data Extraction

A structured extraction matrix was developed to ensure that comparable information was collected from each study. The matrix recorded information as follows:

1. bibliographic information;
2. publication year and journal quartile;
3. geographical and institutional context;

4. research method or design;
5. theory or conceptual framework;
6. actors included in the study;
7. collaboration and governance mechanisms;
8. resources and knowledge exchanged;
9. technological domain;
10. enabling and constraining conditions;
11. technology-development mechanisms;
12. transfer, diffusion, and adoption processes;
13. lifecycle and operational implications;
14. contribution to strategic autonomy; and
15. quality-appraisal score.

The extraction process focused primarily on the findings, analysis, discussion, and conclusions of each article. Technical studies were examined not only for their specific engineering results but also for the broader capability mechanisms they revealed, such as requirements definition, systems integration, testing, validation, maintenance, and technology readiness.

2.5 Thematic Analysis and Synthesis

The extracted data were analyzed through a combined deductive and inductive thematic process. The deductive component was guided by the research question and initially organized around actors, governance, knowledge integration, technology development, transfer, diffusion, operational adoption, lifecycle capability, and strategic autonomy. The inductive component allowed additional mechanisms and relationships to emerge from the studies without being forced into predetermined theoretical categories.

Moreover, the analysis proceeded in three broad stages adapted from thematic-synthesis methodology. First, relevant findings were coded at the study level. Second, related codes were consolidated into descriptive categories that captured recurring patterns across the corpus. Third, the descriptive categories were interpreted to produce higher-order analytical themes and relationships that extended beyond the conclusions of individual studies . The coding process was recursive: categories were repeatedly compared, merged, separated, and refined as new relationships became visible. Code frequency was not used as the sole indicator of analytical importance. A mechanism could be theoretically significant even when it appeared in a limited number of studies, particularly in the technically specialized defense and space literature. Themes were therefore evaluated according to their recurrence, explanatory value, relevance to the research question, support across different evidence categories, and ability to connect institutional collaboration with technological and strategic outcomes.

3. Results

3.1 Profile of The Evidence Base

The analytical corpus consisted of 63 Scopus-indexed studies published between 2019 and 2025. Publication was concentrated in 2020–2023: 18 studies appeared in 2020, 10 in 2021, and 13 each in 2022 and 2023. The journal profile comprised 34 Q1, 21 Q2, and eight Q3 studies. Quality appraisal classified 41 studies as high quality and 22 as moderate quality. The corpus included qualitative and comparative cases, quantitative models, conceptual and bibliometric reviews, policy analyses, engineering simulations, system architectures, and technical demonstrations. This heterogeneity was analytically useful because the research question requires attention both to institutional relationships and to the technical processes through which technologies are developed, transferred, adopted, maintained, and upgraded.

Four evidence categories were used to structure the synthesis. Twenty studies provided core evidence on defense industries, military innovation, dual-use space capabilities, defense procurement, and self-reliance. Twenty-eight studies supplied theoretical or transferable evidence on Helix models, innovation systems, open innovation, stakeholder engagement, and university–industry relations. Twelve studies explained technical mechanisms related to systems engineering, digital twins, prognostics, advanced manufacturing, maintenance, and lifecycle decision-making. Three studies primarily illuminated wider strategic or institutional conditions. Theoretical and transferable studies were therefore the largest group, but the resulting framework was not derived from Helix literature alone. It emerged from the interaction between institutional, defense-industrial, and engineering evidence.

Table 2. Descriptive Profile of the 63 Studies

Dimension	Category	Studies, n	Share
Journal quartile	Q1	34	54.0%
	Q2	21	33.3%
	Q3	8	12.7%
Evidence role	Theoretical/transferable evidence	28	44.4%
	Core defense and space evidence	20	31.7%
	Technical mechanism evidence	12	19.0%
	Contextual enabling evidence	3	4.8%
Quality category	High	41	65.1%
	Moderate	22	34.9%
Publication period	2019–2021	31	49.2%
	2022–2025	32	50.8%

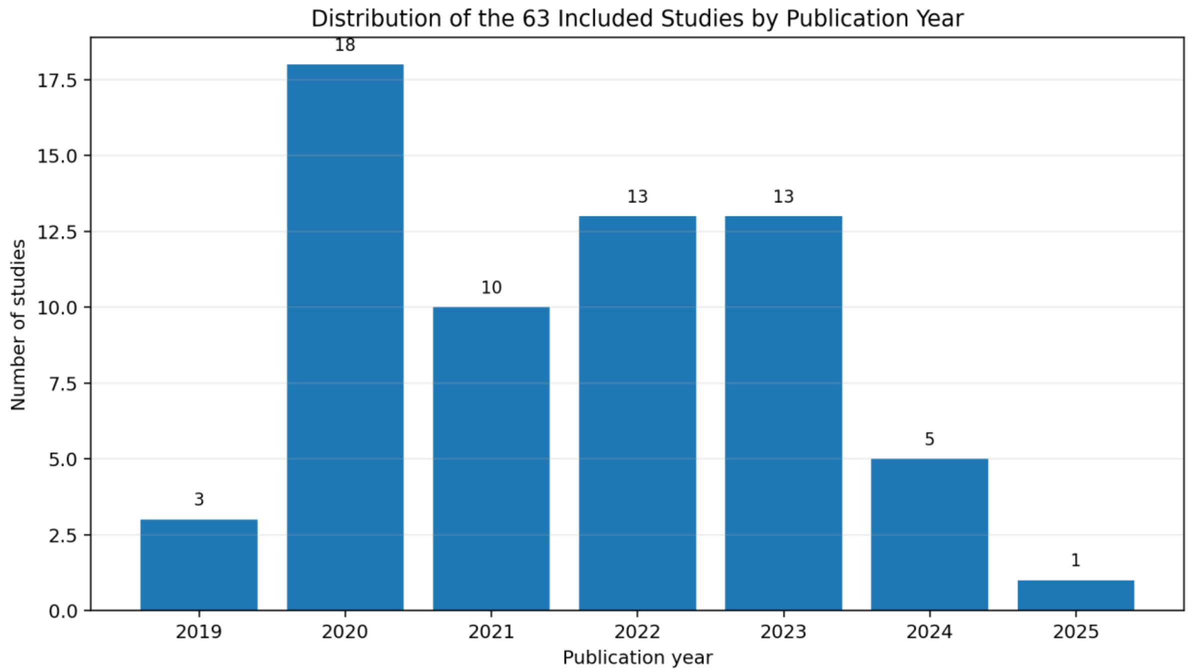

Figure 1. Distribution of the 63 Included Studies by Publication Year

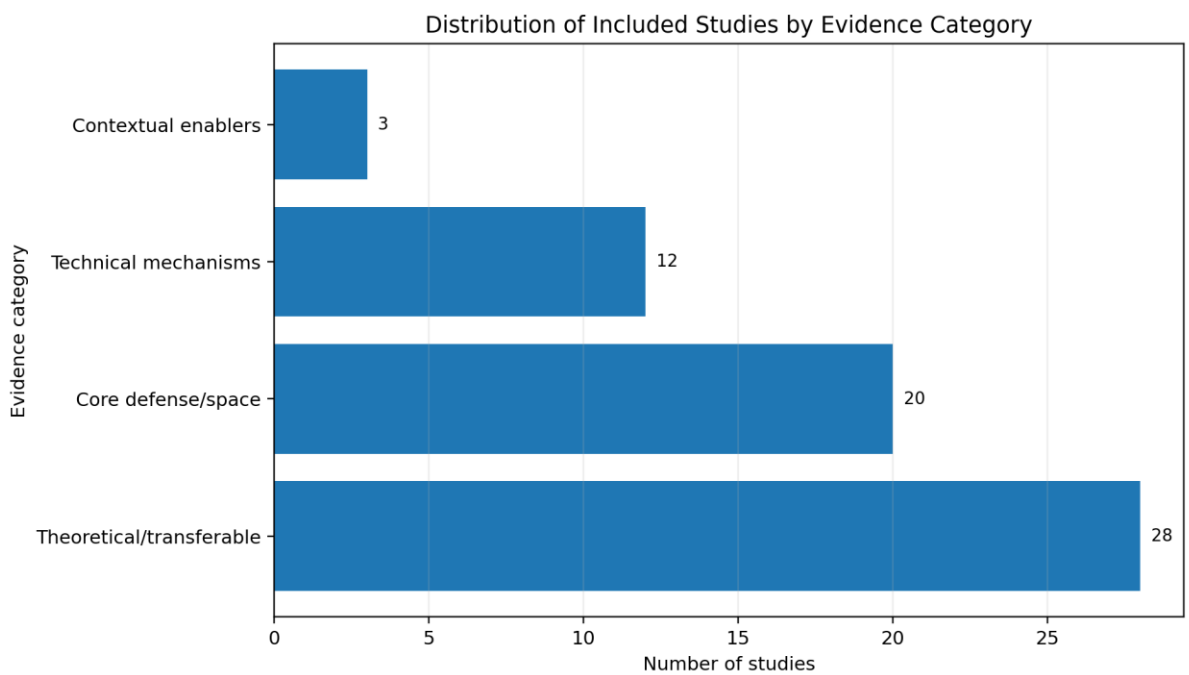

Figure 2. Distribution of the Included Studies by Evidence Category

The evidence also revealed a persistent imbalance in the literature. Institutional studies frequently described actors, partnerships, and governance mechanisms but did not trace their effects through engineering development and operational adoption. Conversely, technical studies offered detailed accounts of architecture, readiness, verification, and maintenance but rarely examined the institutional ecosystem that makes such capabilities possible. This divide became the central analytical problem addressed by the thematic synthesis, as follows:

3.2 Theme 1: Ecosystem Governance and Orchestration

The first theme concerned the capacity to align actors around a shared technological direction. Across the literature, collaboration was most effective when an institution or coalition performed an orchestration function: articulating priorities, connecting organizations, allocating responsibilities, sustaining resources, and resolving conflicts. showed that weak links among higher education, government, and the private sector can persist even when all three actors formally belong to the same national innovation system. The problem was not the absence of organizations but fragmented incentives, limited trust, and insufficiently institutionalized channels for cooperation.

Extended-Helix studies reinforced this finding. The Hexa-Helix framework presented by broadened the actor structure beyond the traditional university–industry–government relationship, while later applications emphasized participation, information sharing, and complementary responsibilities in complex risk environments . Collaborative-governance research similarly indicated that structural and non-structural measures produce stronger outcomes when decision-making, community knowledge, infrastructure, and institutional authority are connected rather than implemented separately . These studies were not defense-specific, but they exposed a transferable principle: complex technological systems require coordination across technical and social subsystems.

The literature also identified the limits of formally inclusive governance. In a penta-helix participatory program, vertical hierarchies and organizational "downpipes" prevented knowledge from circulating across actor groups, despite an explicit commitment to collaboration . likewise found that civil-society participation in regional innovation planning depends on facilitation and institutional access, not simply invitations to participate. Interactive research provides one possible response because it creates repeated cycles of joint problem definition, knowledge production, and learning between researchers and practitioners . However, such arrangements require time, continuity, and agreed rules regarding ownership and use of knowledge.

A systems perspective further clarified why orchestration matters. demonstrated that innovation ecosystems combine technological assets with policies, finance, talent, firms, research institutions, and market formation. showed that mapping actor relationships and feedback mechanisms can reveal policy levers that remain invisible in linear innovation models. Cluster-evaluation research reached a similar conclusion: evaluation should capture network formation, learning, and new collaborative capacity rather than only short-term outputs . In the defense context, governance is additionally shaped by civil–military authority and the institutional position of the armed forces. showed that formal civilian supremacy does not necessarily eliminate military dominance inside defense institutions, which may affect transparency, industrial priorities, and the distribution of decision rights.

Taken together, these findings suggest that an ecosystem orchestrator must perform five functions. It must translate national strategy into a limited set of technology priorities; connect research, industrial, financial, and user organizations; establish decision and accountability mechanisms; maintain continuity across budget and political cycles; and manage the tension between openness for innovation and restrictions arising from security, export control, and intellectual property. Government is usually best placed to provide strategic authority, but orchestration need not mean direct state control over every activity. It is better understood as the capability to create the conditions under which distributed actors can produce a coherent technological result.

3.3 Theme 2: Actor Configuration and Collaborative Mechanisms

The second theme concerned which actors matter and how their roles should be configured. The Triple Helix remains the dominant conceptual starting point, but the reviewed studies repeatedly showed that the value of the model lies in interaction among institutional spheres rather than in a fixed list of three actors. Open-innovation research places universities in a central knowledge-generating role, while also showing that commercialization and application require strong links to firms and public institutions . University–industry collaboration can produce technological, organizational, and socioeconomic benefits, but these benefits vary according to the form of collaboration and the capacities of the participating organizations .

The evolution toward wider Helix models reflects dissatisfaction with arrangements that exclude users, citizens, intermediaries, finance, and sustainability concerns. argued that innovation and wider public objectives may require interacting institutional configurations rather than an endlessly expanded single helix. N-Helix research during the COVID-19 crisis illustrated how digital platforms enabled social entrepreneurs, public authorities, communities, and technical actors to respond to urgent stakeholder needs . similarly showed that a Triple-Helix configuration can support the diffusion of advanced manufacturing such as three-dimensional printing when universities, government, and firms jointly develop skills, infrastructure, and market applications.

Participation mechanisms matter because actors enter collaborations with different expectations. Living-lab research found that stakeholders may value access to networks, testing environments, legitimacy, or learning differently, and dissatisfaction arises when promised co-creation is replaced by consultation without influence . Quantitative evidence from Spanish technology companies showed that Triple-Helix interaction is associated with sustainable innovation, although effects depend on the institutional and sectoral environment . National innovation-system evidence from Poland likewise indicated that the structure and intensity of science–industry–government relations vary across firms and regions, limiting the usefulness of uniform policy prescriptions . Bibliometric analysis confirmed that Triple-Helix research has diversified into regional innovation, entrepreneurship, sustainability, and extended actor configurations, but also remains conceptually fragmented .

Specific studies also clarify actor functions. Universities can serve as ecosystem integrators and trusted conveners rather than only as research suppliers . Efficient Triple-Helix collaboration can improve R&D performance, although the benefit differs by organizational growth stage . Industrial doctorates embed knowledge exchange and human-capital development within industry–university–government relations , while communities and intermediaries can transmit ecosystem benefits to smaller firms .

For defense-space technology, six functions must be covered. Government provides strategy, regulation, procurement, and risk absorption; industry converts knowledge into manufacturable and supportable systems; universities and research institutions supply knowledge, personnel, and independent technical capability; users define missions and validate performance; financial bodies provide patient capital; and media, civil society, and intermediaries support legitimacy and coordination. International partners cut across these functions through technology, standards, markets, and supply chains. This actor structure should not be interpreted as a universal numerical Hexa-Helix formula. Its value is functional. A defense-space ecosystem becomes effective when each essential function is performed, responsibilities are clear, and interfaces are institutionalized. Adding actors without clarifying authority, incentives, and resource commitments can increase transaction costs. Conversely, excluding users, finance, or system integrators may leave apparently strong research collaborations unable to produce operational capability.

Table 3. Functional Roles in a Defense-Space Innovation Ecosystem

Actor group	Primary functions	Typical failure when weak or absent
Government and public agencies	Strategic direction, regulation, procurement, long-term funding, export-control and IP governance	Fragmented priorities, short project cycles, policy–capability mismatch
Defense and space industry	Product development, systems integration, manufacturing, supply-chain and lifecycle support	Prototypes that cannot be industrialized or sustained
Universities and research institutions	Scientific knowledge, testing, specialist facilities, human-capital development	Limited absorptive capacity and weak indigenous knowledge base

Military and operational users	Requirement definition, operational validation, doctrine, training, lessons learned	Technology–mission mismatch and low adoption
Finance and funding institutions	Patient capital, risk sharing, commercialization and scale-up finance	"Valley of death" between research, demonstration, and production
Media, civil society and intermediaries	Legitimacy, communication, facilitation, demand articulation and societal oversight	Low trust, weak coordination and limited public support
International partners	Technology access, co-development, standards, markets and supply-chain linkages	Isolation when absent; dependency and bargaining asymmetry when dominant

3.4Theme 3: Knowledge, Resources, and Absorptive Capacity

The third theme concerned the mechanism that converts collaboration into capability. Across the corpus, knowledge exchange alone was insufficient. Innovation outcomes depended on the recipient's ability to identify useful knowledge, combine it with existing competencies, and apply it in production or operations. highlighted absorptive capacity and purposeful upgrading as requirements for translating participation in global value chains into industrialization. In university–industry collaboration, structured planning, common expectations, and explicit mechanisms for exchanging personnel and knowledge are similarly necessary . showed that technology-transfer relationships are weakened by limited institutional support, inadequate incentives, communication problems, and the absence of effective intermediary structures.

The synthesis identified four resource flows that must be integrated. The first is knowledge: scientific findings, tacit engineering expertise, data, design rules, standards, and operational lessons. The second is human capital: researchers, engineers, maintainers, acquisition specialists, and users capable of working across organizational boundaries. The third is physical and digital infrastructure: laboratories, simulation environments, test ranges, secure data systems, integration facilities, and production assets. The fourth is finance: research grants, development budgets, industrial investment, procurement commitments, and support for scaling technology from prototype to operational system.

Evidence on corporate digital transformation demonstrated that digitalization can enhance innovation, but the effect depends on organizational capability rather than technology acquisition alone . Dynamic-capability research in Brazil's defense industry reached the same conclusion from a strategic-management perspective: firms must sense changes, seize opportunities, and reconfigure assets in alignment with national defense objectives . Civil–military integration in China further showed that civilian firms require measurable manufacturing, innovation, quality, and security capabilities before entering military markets. Thus, absorptive capacity is not a vague cultural attribute; it is expressed through personnel, processes, quality systems, facilities, security compliance, and prior knowledge.

Defense-sector studies showed how these flows can be institutionalized. Portugal's open-innovation approach sought to connect defense organizations with firms and knowledge institutions to increase military capability . The Portuguese Triple-Helix analysis also revealed that state leadership and knowledge-society mechanisms coexist rather than replace one another, with defense projects drawing on government, industry, academia, and dual-use relationships . Cross-country evidence linked university–industry R&D collaboration to innovation and quality standards, suggesting that collaboration becomes more valuable when it is embedded in organizational systems capable of codifying and assuring knowledge .

These findings support a mediating interpretation: collaboration affects technological outcomes through knowledge and resource integration. Meetings, memoranda, and stakeholder lists do not create capability unless they lead to shared work packages, personnel mobility, access to facilities, data exchange, common standards, and cumulative learning. For defense-space technology, this integration must also operate under security constraints. The challenge is therefore to design differentiated access that is open enough to allow innovation, but controlled enough to protect classified knowledge and critical technology.

3.5Theme 4: Defense-Space Technology Development and Lifecycle Capability

The fourth theme emerged primarily from the technical-mechanism evidence. These studies showed that technology development is a lifecycle process rather than a single act of invention. proposed a systematic architecture methodology for prognostics and health-management systems, emphasizing the translation of stakeholder needs into system functions, architecture, verification, and validation. Their related requirements methodology showed that predictive-maintenance capability depends on clear operational use cases and properly defined information needs before technology selection begins . This is directly relevant to defense-space programmes, where poorly defined requirements can produce systems that are technically sophisticated but operationally unsuitable.

Digital-twin research illustrated the importance of integration across design, testing, operation, and maintenance. examined the adaptability and demonstration of airframe digital-twin technology, while presented digital twins as an aerospace capability linking physical assets, models, data, and lifecycle decisions. Fleet-level research extended this logic by showing how digital twins can support condition monitoring and more intelligent maintenance across multiple aircraft rather than a single component . The common mechanism is a persistent digital representation that captures configuration and condition over time. For satellite and defense-space systems, this suggests that data architecture and configuration management should be treated as sovereign capabilities, not merely software features.

Maintenance studies added an organizational dimension. Augmented-reality manuals require reliable technical data and integration with work processes . Condition-based maintenance can improve availability, but depends on data quality, certification, user trust, and coordination between engineering and operations . Prescriptive maintenance must demonstrate economic value . Lifecycle simulation can compare technology, maintenance, and operational alternatives before commitment .

Prognostics and system-health management further highlighted the need for mission assurance. found that modeling approaches differ in data requirements, interpretability, and applicability, making hybrid and context-specific methods preferable to universal algorithms. showed that integrated system-health management can combine diagnostics, prognostics, artificial intelligence, and mission-management functions for safety-critical aerospace systems, including distributed satellites. These capabilities connect engineering health information to operational choices, thereby reducing the separation between technical maintenance and mission command.

Technology maturation also requires attention to interacting constraints. All-electric aviation combines challenges in energy storage, thermal management, safety, certification, and infrastructure . Additive manufacturing offers weight and lead-time advantages but still faces repeatability and certification problems . AI and robotics can accelerate aerospace and defense functions, while increasing requirements for validation, cyber resilience, data governance, and human oversight .

The technical synthesis therefore identified a recurring development pathway: requirement definition; research and design; prototyping; verification and validation; systems integration; production readiness; operational introduction; maintenance; and upgrading. The stages are iterative rather than strictly sequential. Data from tests and operations feed back into design, while supply-chain and maintenance constraints may require architectural changes. A country that can assemble a prototype but cannot validate, certify, integrate, maintain, or upgrade it possesses a demonstration, not a sustainable capability.

3.6Theme 5: Defense-Industrial Transformation, Transfer, and Self-Reliance

The fifth theme connected the previous mechanisms to defense-industrial and strategic outcomes. In developing-country defense industries, technological innovation and organizational systems affect firm performance and the ability to support national objectives . However, country cases showed that industrial capability is shaped by long-term institutional histories. The Czech defense industry illustrates the consequences of weak demand, fragmented ownership, limited investment, and uncertain state policy . Iran's defense industry demonstrates that political commitment and perceived security necessity can support indigenous production, but opacity, technological constraints, and limited access to external inputs complicate objective assessment .

Small-state evidence shows that significant military innovation is possible through niche specialization, government–industry integration, human capital, and international networks . Türkiye's expansion similarly reflects political, industrial, and academic interaction, although sustainability depends on technological depth and institutional quality . South Korea illustrates both the upgrading opportunities and structural tensions created by globalized arms production .

Indonesia's experience confirms that self-reliance requires more than domestic ownership. Industrial performance, innovation capacity, government support, market access, and supply-chain development must reinforce one another . Procurement design is therefore critical. Belgium's naval-construction cluster illustrates how defense acquisition can be used to organize domestic industrial participation and knowledge relationships, but cluster benefits depend on credible demand, coordination, and long-term work allocation . The Brazilian Army case showed how Triple-Helix and open-innovation principles can be institutionalized inside a defense organization to connect operational problems with research and industry .

Finance is another strategic variable. showed that financial-market pressure and consolidation can reshape the behavior and structure of defense contractors. Concentration may provide scale and capital, but it can reduce competition, narrow the supplier base, and increase state dependence on a small number of firms. This finding complements the earlier ecosystem evidence: financial institutions are not peripheral actors because the structure of capital influences which technologies survive long development cycles and which firms retain the capacity to innovate.

International cooperation has mixed effects. Japan has adapted trade, aid, and dual-use technology to strategic aims , while its space situational-awareness programme shows the difficulty of combining civilian expertise, defense missions, and alliance requirements . India's partnerships with Russia and France support diversification, transfer, co-development, and co-production, but do not automatically remove dependence . Arms-export reform is likewise constrained by manufacturing weakness, foreign technology, and limited military R&D finance .

The central result is that technology transfer contributes to self-reliance only when it changes domestic capability. Delivery of equipment, training, or documentation is not enough. The recipient must be able to absorb knowledge, integrate systems, maintain readiness, reproduce selected components, modify software and hardware, manage supply chains, and develop subsequent generations. Self-reliance is therefore better treated as a cumulative capability continuum than a binary distinction between import and domestic production.

3.7 Integrated Conceptual Framework

The thematic synthesis produced an eight-layer framework. Strategic and institutional enablers form the first layer: national priorities, regulation, procurement, long-term finance, international policy, and intellectual-property and security governance. The second layer is the collaborative innovation ecosystem, composed of the functional actor groups identified above. The third layer contains alignment mechanisms such as shared roadmaps, joint decision-making, consortia, collaborative research, co-development, risk sharing, and user participation.

The fourth layer, which is knowledge and resource integration, is the principal mediating mechanism. It includes absorptive capacity, human capital, infrastructure, finance, data, standards, and organizational learning. These resources enable the fifth layer: defense-space technology development through requirements, R&D, prototyping, integration, verification, and production readiness. Technology transfer and diffusion form the sixth layer, followed by operational adoption and lifecycle capability in the seventh. Sovereign defense-space capability is the strategic outcome in the eighth layer. The framework includes a feedback loop because operational experience, maintenance findings, mission changes, and technological failures reshape requirements and direct further R&D. It therefore rejects a simple pipeline in which research automatically becomes capability. Defense-space innovation is an iterative process in which institutions, technology, and operations co-evolve.

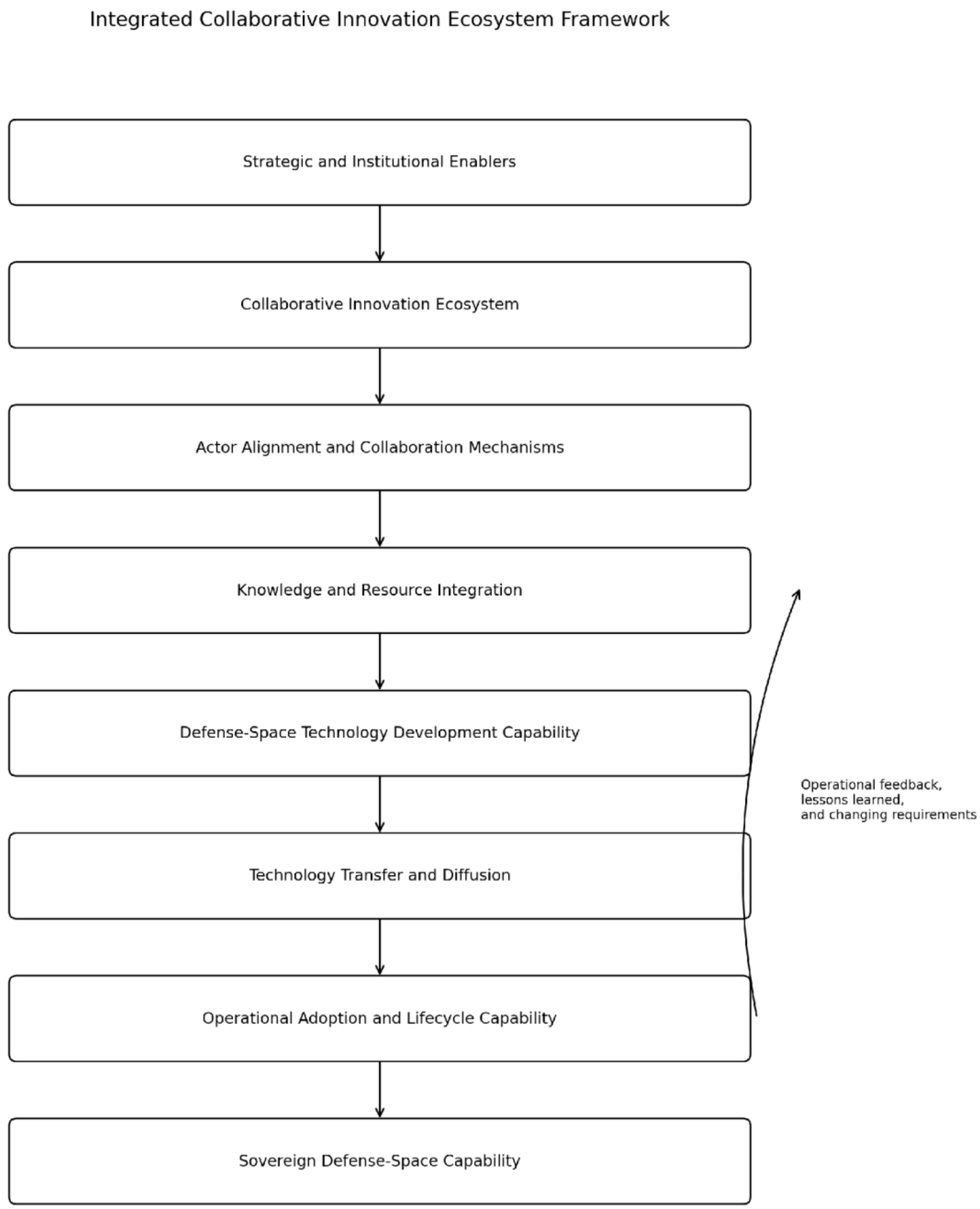

Figure 3. Distribution of the Included Studies by Evidence Category

Table 4. Thematic Synthesis and Integrated Pathway

Analytical Theme	Central Mechanism	Immediate Output	Contribution to Sovereign Capability
Governance and orchestration	Alignment of priorities, authority, incentives and accountability	Coherent ecosystem direction	Reduced fragmentation and policy–capability mismatch
Actor configuration	Complementary and institutionalized roles	Stable collaboration architecture	Access to mission, knowledge, production, finance and legitimacy functions
Knowledge and resource integration	Absorptive capacity, shared infrastructure, personnel and finance	Collective technological capability	Domestic ability to understand, integrate and adapt technology
Technology development	Requirements, systems engineering, testing and industrialization	Validated and supportable systems	Control over critical design and integration decisions
Transfer and diffusion	Co-development, learning, replication and organizational spread	Localized knowledge and broader adoption	Reduced external dependence and increased upgrading capability
Operational and lifecycle capability	Doctrine, training, maintenance, data, configuration and feedback	Sustained mission readiness	Operational freedom and cumulative innovation

4. Discussion

4.1 From Actor Presence to Ecosystem Functionality

The review's first theoretical contribution is to distinguish actor presence from ecosystem functionality. Much of the Helix literature begins by identifying which institutional spheres are represented. This is useful for mapping participation, but it can create an implicit assumption that a larger number of actors indicates a more advanced ecosystem. The evidence does not support that assumption. Collaborations failed when responsibilities were unclear, hierarchies blocked horizontal communication, or participation did not provide real influence. Conversely, smaller configurations sometimes generated strong outcomes when partners shared problems, resources, and decision rights. Three analytical levels should therefore be separated. Actor presence refers to whether government, industry, academia, users, finance, civil society, and international partners exist in the relevant policy space. Actor interaction concerns communication, projects, contracts, and network ties. Actor integration occurs when these interactions alter the distribution and combination of knowledge, resources, infrastructure, and capability. Only the third level explains how collaboration changes technological outcomes.

This distinction helps resolve a recurring weakness in extended-Helix models. The practical question is not whether a defense-space ecosystem should be called a Triple, Quadruple, Quintuple, or Hexa Helix. The more important question is whether all essential functions are performed and connected. Military users, for instance, may formally belong to government, but analytically they should remain distinct because they contribute mission requirements, doctrine, operational risk, and feedback that civilian ministries do not possess. Finance may not appear in every project team, but it shapes whether technologies cross the "valley of death." International partners may enable access to knowledge and markets while simultaneously increasing dependency risk. A functional approach is thus more informative than a numerical one.

The framework also revises the role of government. State leadership and ecosystem governance should not be treated as opposites. Defense-space technology involves sovereignty, classified information, large fixed costs, and uncertain commercial demand, which make government direction unavoidable. Yet direct control without distributed learning can suppress innovation. Effective orchestration combines strategic state capacity with decentralized technical work, competitive experimentation, and institutionalized user–industry–research collaboration.

4.2 Extending Helix Theory for Defense-Space Innovation

The second contribution is a context-specific extension of Helix theory. Conventional models were developed primarily to explain knowledge-based regional and economic development. Defense-space innovation shares some of these mechanisms but introduces additional constraints. Security classification limits information flows; export controls restrict technology access; procurement rules shape demand; failure has mission and national-security consequences; and lifecycle support may be required for decades. These conditions alter actor incentives and make trust, security accreditation, and long-term commitment particularly important.

A defense-space Helix should therefore be organized around functions rather than labels. Government acts as strategist, regulator, buyer, funder, and security guardian. Industry combines efficiency with secure supply and long-term support. Research organizations reconcile scientific openness with controlled work. Users prevent requirement drift without foreclosing experimentation. Financial actors accept long payback periods, while intermediaries translate across professional and institutional boundaries.

This functional extension also highlights the importance of the "system integrator." Many countries can develop individual components but remain dependent on foreign entities for architecture, software, interfaces, certification, and mission integration. The integrator position is strategically powerful because it controls how components become a system. In a satellite programme, that role may include spacecraft, payload, ground segment, data processing, communications, cybersecurity, and user applications. Building sovereign capability therefore does not require immediate domestic production of every component. It requires control over critical architecture and interfaces, sufficient knowledge to evaluate imported technology, and the ability to replace, adapt, or upgrade selected elements.

The media and civil-society function should also be interpreted carefully. Defense-space programmes cannot operate with the same transparency as ordinary regional innovation projects. Nonetheless, legitimacy, public understanding, and political continuity remain important, particularly for expensive long-term programmes. The appropriate role is not unrestricted access to classified information, but informed communication, accountability at the policy level, and support for a national technology narrative that extends beyond individual procurement decisions.

4.3 Bridging Institutional and Technical Explanations

The third contribution is the integration of institutional collaboration with technical development and lifecycle capability. Existing research often ends too early. Innovation studies may identify networks and knowledge transfer but stop before verification, integration, and operational use. Engineering studies may demonstrate a digital twin, maintenance algorithm, or manufacturing process without explaining how institutions finance, govern, and absorb it. The framework connects these literatures through the mediating concept of knowledge and resource integration.

This connection changes how technology development should be evaluated. Conventional indicators such as research spending, publications, patents, prototypes, or local-content percentages, capture only parts of the process. A more complete assessment should consider requirement ownership, architecture competence, access to design data, systems-integration capability, test and certification capacity, production repeatability, maintainability, software control, supply-chain resilience, and the ability to learn from operational data. These indicators reveal whether a programme is accumulating capability or merely completing a contract.

Lifecycle evidence is especially important for defense-space systems. Satellites and associated ground infrastructure cannot be treated as products that are complete at delivery. Their mission performance depends on software updates, calibration, anomaly resolution, data exploitation, cyber protection, operator proficiency, and replenishment planning. Digital twins and health-management systems can support these tasks, but only if the state or domestic ecosystem retains access to trusted data, models, configuration records, and engineering authority. Otherwise, sophisticated digital technologies may deepen dependency by centralizing knowledge in the foreign supplier.

The synthesis also shows why operational adoption should be treated as a distinct stage. A technology may be technically mature yet fail to become capability because doctrine, training, organization, infrastructure, and user trust are absent. Early user participation is therefore necessary, but it must be structured. Users should define mission effects and operational constraints rather than prescribe a specific technical solution before alternatives are explored. This protects innovation while keeping development connected to real missions.

4.4 Rethinking Defense Self-Reliance and Strategic Autonomy

The fourth contribution is a multidimensional interpretation of self-reliance. Autarky is neither realistic nor necessarily desirable in a sector characterized by global supply chains and rapid technological change. Complete domestic production can consume scarce resources and isolate firms from international knowledge. At the same time, unmanaged dependence can expose operations to political restrictions, disrupted supply, unavailable software keys, maintenance delays, and loss of decision freedom.

The evidence supports six cumulative levels: operational autonomy, or independent mission use; maintenance autonomy, or domestic diagnosis and readiness restoration; integration autonomy, or architectural control over subsystems, software, and data; production autonomy, or manufacture at required quality and scale; innovation autonomy, or modification and next-generation development; and strategic autonomy, or freedom from unacceptable external technological leverage.

These levels are related but not identical. A country may operate imported equipment independently, manufacture licensed components without design authority, or maintain a platform while depending on foreign software. Local content is therefore inadequate as a stand-alone measure; policy should specify the autonomy level required for each critical mission and technology.

International cooperation remains compatible with this model. Co-development and co-production can accelerate learning when domestic actors receive substantive engineering responsibility, access to data, and opportunities to make design decisions. Partnerships are less transformative when local participation is confined to assembly, low-value manufacturing, or short training courses. Diversification can reduce reliance on one supplier, but managing several incompatible foreign systems may also increase lifecycle complexity. Cooperation should thus be evaluated by its contribution to domestic absorptive capacity, architecture control, supply resilience, and future innovation, not solely by the immediate acquisition of equipment.

4.5 Policy and Managerial Implications

The framework has several implications for governments and organizations developing defense-space capabilities. First, national strategy should identify a small number of critical capabilities rather than declare universal technological independence. Priorities may include mission architecture, secure communications, payload data processing, ground-control software, space situational awareness, systems integration, or selected satellite components. Concentrating resources allows cumulative learning and reduces symbolic programs that remain technologically shallow.

Second, procurement should be designed as an innovation and learning instrument. Contracts can require joint engineering teams, access to technical data, domestic test participation, training linked to real work packages, and measurable transfer outcomes. Offset value should be assessed by capability acquired rather than nominal financial value. Procurement, research funding, industrial policy, and human-capital planning should be governed through a common roadmap.

Third, shared infrastructure is essential. Laboratories, environmental test facilities, secure digital engineering environments, integration centers, and simulation platforms are expensive and may be underused when owned separately. Shared national facilities can connect universities, firms, and users while maintaining security through tiered access.

Fourth, long-term financing must bridge research, demonstration, certification, and early production. A promising prototype should not fail because funding mechanisms change before industrialization.

Fifth, performance measurement should move from activity to capability. Relevant indicators include technology-readiness progression, percentage of requirements verified domestically, domestic control of interfaces and software, mean time to restore systems, supplier concentration, availability of qualified personnel, number of jointly completed engineering work packages, reuse of knowledge across programs, and the ability to implement upgrades without original-supplier dependence.

4.6 Limitations and Future Research

The study is based on a purposively curated corpus and does not claim exhaustive coverage of all defense-space innovation literature. The inclusion of transferable studies from disaster governance, regional planning, smart cities, and wider innovation systems increases theoretical breadth but requires caution when applying findings to classified and mission-critical environments. The corpus also combines different methodological traditions, which limits direct comparison of effect sizes. The thematic synthesis identifies mechanisms and relationships, not universally applicable causal magnitudes.

Future research should empirically test the integrated framework. Comparative case studies could examine how different countries allocate the ecosystem-orchestrator role. Social-network analysis could measure actor centrality, knowledge flows, and structural gaps. Longitudinal studies could follow specific technology-transfer programmes from contract signature through maintenance and upgrading. Quantitative research could operationalize governance, collaboration quality, absorptive capacity, technology development, diffusion, and autonomy and test the proposed pathway through structural-equation modeling. A defense-space autonomy index could also distinguish operational, maintenance, integration, production, innovation, and strategic dimensions. The review shows that defense-space capability is not produced by a single institution, a technology-transfer clause, or an isolated research project. It emerges when strategic governance aligns complementary actors; collaboration integrates knowledge, people, finance, and infrastructure; and those resources are converted through systems engineering, industrialization, operational adoption, and lifecycle learning. The key analytical shift is from counting actors and domestic components to examining whether the ecosystem can understand, integrate, operate, sustain, and further develop critical technology.

The resulting framework treats sovereign defense-space capability as an iterative and layered outcome. International cooperation remains important, but its strategic value depends on what domestic organizations learn and can subsequently control. In this sense, self-reliance is not withdrawal from global technology networks. It is the capacity to participate in those networks without surrendering essential freedom of action.

5. Summary

This research examined how collaborative innovation ecosystems contribute to the development, transfer, diffusion, operational adoption, and long-term sustainment of defense-space technologies. Drawing on an integrative review of 63 Scopus-indexed studies, the analysis shows that defense-space capability cannot be built through isolated research projects, stand-alone procurement programs, or the efforts of a single institution. It emerges from a coordinated ecosystem in which government, defense industry, universities, research institutions, military users, financial actors, innovation intermediaries, and international partners contribute different but complementary resources.

A central finding is that the presence of multiple actors does not automatically create an effective innovation ecosystem. Collaboration becomes meaningful only when relationships are institutionalized and translated into shared priorities, coordinated decisions, knowledge exchange, joint research, infrastructure sharing, and sustained financing. The distinction between actor presence, actor interaction, and actor integration is therefore important. Many innovation initiatives succeed in bringing institutions into the same forum but fail to create the mechanisms needed to integrate their resources and capabilities. In defense-space development, this gap can result in fragmented research, duplicated investment, unclear technological priorities, and continued dependence on external suppliers.

The review also identifies knowledge and resource integration as the main mechanism linking collaboration with technological outcomes. Defense-space systems require more than scientific knowledge or manufacturing capacity. They depend on systems engineering, software and hardware integration, testing, certification, skilled personnel, data infrastructure, maintenance capability, and organizational learning. These capabilities are distributed across institutions and must be combined over time. Absorptive capacity is especially important because access to foreign technology does not necessarily lead to domestic mastery. Technology becomes strategically valuable only when recipient organizations can understand, reproduce, adapt, integrate, maintain, and further develop it.

Another important conclusion is that technology development, technology transfer, diffusion, and operational adoption should not be treated as separate processes. A prototype may demonstrate technical feasibility without becoming an operational capability. Similarly, transferred equipment or technical documentation may have limited strategic value if the technology cannot be integrated into domestic systems, supported through its lifecycle, or adapted to changing operational needs. The proposed framework therefore connects research and development with technology maturation, transfer, diffusion, organizational adoption, maintenance, upgrading, and feedback from operational experience. This creates an iterative innovation cycle in which lessons from use inform future requirements and technological improvement.

The findings also suggest that sovereign defense-space capability should not be equated with complete technological self-sufficiency. Full autarky is neither realistic nor necessarily efficient in a sector characterized by global supply chains, high costs, and rapid technological change. Sovereignty is better understood as a progressive capability to make independent strategic decisions, manage critical dependencies, operate and sustain essential systems, integrate technologies from different sources, and develop selected critical technologies domestically. This view allows international cooperation to remain part of national capability development while emphasizing the need to avoid forms of dependence that could undermine operational readiness or strategic freedom.

The integrated framework developed in this study places strategic and institutional enablers at the beginning of the capability-building process. Clear national priorities, consistent regulation, long-term funding, coordinated procurement, intellectual-property arrangements, and capable ecosystem orchestration are necessary to align actors and reduce uncertainty. These conditions support collaboration, knowledge integration, technology development, diffusion, and lifecycle capability. The framework also highlights the distinct role of military users, whose early involvement is essential for translating operational needs into technological requirements and ensuring that innovation produces usable defense capability.

All in all, this study contributes a more complete explanation of how collaborative innovation ecosystems can support defense-space capability development. Its main implication is that policy should move beyond measuring the number of partnerships or institutions involved. Greater attention should be given to the quality of coordination, the integration of knowledge and resources, the development of absorptive and systems-integration capabilities, and the connection between innovation, operations, and lifecycle sustainment. Future empirical research can test these relationships across national contexts and identify which ecosystem configurations are most effective for countries seeking to strengthen their defense-space autonomy.

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