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# MULTIMODAL EDUCATION ENTREPRENEURSHIP NETWORKS AND INTELLECTUAL CAPITAL FORMATION DYNAMICS

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***ABSTRACT*:**

The objective of this study was to examine the relationships among multimodal education, university entrepreneurship, and intellectual capital formation through the specification and testing of a network model using Gephi. A quantitative, cross-sectional, exploratory, and correlational design was implemented with a sample of 300 university students participating in multimodal learning environments. The proposed model integrated Multimodal Education, Entrepreneurial Competencies, Innovation Orientation, Knowledge Management, Collaborative Learning, Human Capital, Structural Capital, and Relational Capital. Data were collected using a validated instrument composed of sixty indicators distributed across the principal dimensions of the model. Reliability, validity, and network analyses were conducted to evaluate the structural properties of the proposed framework.

The findings revealed significant positive relationships among all variables. Multimodal Education demonstrated strong connections with Collaborative Learning, Entrepreneurial Competencies, and Human Capital. Entrepreneurial Competencies exhibited substantial associations with Innovation Orientation, Human Capital, and Relational Capital. Knowledge Management emerged as a central mechanism influencing Human Capital and Structural Capital. Collaborative Learning functioned as a strategic intermediary process facilitating knowledge exchange and competency development. Human Capital occupied the most influential position within the network, while Relational Capital represented the primary destination of knowledge flows. Network metrics indicated high density, strong clustering, and interconnected community structures, supporting the existence of an integrated entrepreneurial ecosystem.

The results suggest that intellectual capital formation is a multidimensional and networked process supported by educational innovation, entrepreneurial development, collaborative interaction, and knowledge management practices. The Gephi model provided evidence that multimodal educational environments contribute directly and indirectly to the development of entrepreneurial capabilities and intellectual capital dimensions. The study advances understanding of university entrepreneurship from a network perspective and offers methodological and practical implications for educational institutions seeking to strengthen innovation, knowledge creation, and sustainable intellectual capital development.

***Keywords**: Multimodal Education, University Entrepreneurship, Intellectual Capital, Knowledge Management, Network Analysis*

## INTRODUCTION

The transition toward knowledge-based economies has transformed universities into strategic environments for the generation, dissemination, and application of knowledge. Within this context, university entrepreneurship has emerged as a critical mechanism for converting scientific knowledge, technological capabilities, and innovative competencies into social and economic value. The increasing integration of digital technologies into educational processes has accelerated the adoption of multimodal education, understood as the combination of textual, visual, auditory, interactive, and collaborative learning environments designed to enhance learning outcomes and entrepreneurial competencies among university students (1,2).

Recent studies suggest that entrepreneurial education is no longer limited to business creation or venture management but extends to the development of intellectual capital through the acquisition of knowledge, skills, attitudes, networks, and innovation capabilities (3,4). Intellectual capital has been conceptualized as the


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combination of human, structural, and relational resources that enable organizations and individuals to create value through knowledge-intensive activities (5). In university contexts, multimodal educational environments contribute to intellectual capital formation by facilitating knowledge acquisition, collaborative learning, digital literacy, innovation, and entrepreneurial self-efficacy (6,7).

Despite growing evidence regarding the positive effects of entrepreneurial education and digital learning environments, significant theoretical and methodological challenges remain. First, the epistemological foundations of university entrepreneurship continue to be fragmented across constructivist, sociocultural, human capital, innovation systems, and knowledge management perspectives (8,9). Second, theoretical approaches often differ regarding the causal relationships among entrepreneurial learning, intellectual capital development, technological mediation, and innovation outcomes. Third, empirical studies frequently employ isolated variables without considering the complex network structures that characterize entrepreneurial ecosystems within higher education institutions (10).

From an epistemological perspective, constructivist approaches emphasize the active role of learners in knowledge creation through interaction with multimodal resources and collaborative environments (11). Sociocultural perspectives highlight the importance of social networks, institutional contexts, and communities of practice in entrepreneurial learning processes (12). Human capital theory proposes that educational investments increase productivity and entrepreneurial capacity through the accumulation of knowledge and competencies (13). Meanwhile, intellectual capital theory suggests that value creation depends on the interaction among human, structural, and relational assets embedded within organizational systems (5).

Theoretical developments have generated several conceptual models linking multimodal education and entrepreneurship. These models generally assume that digital learning environments enhance entrepreneurial competencies, innovation capabilities, knowledge transfer processes, and network formation, thereby strengthening intellectual capital accumulation (14,15). However, the multidimensional nature of these relationships requires analytical frameworks capable of representing complex interactions among actors, resources, competencies, and institutional mechanisms.

Network analysis offers a promising methodological alternative for addressing these challenges. In particular, Gephi-based models facilitate the visualization and measurement of relational structures among variables, constructs, indicators, and actors involved in entrepreneurial ecosystems (16). Through network metrics such as degree centrality, betweenness, modularity, clustering coefficients, and density, Gephi models allow researchers to identify strategic nodes, influential relationships, and emerging patterns within intellectual capital formation processes (17).

The present study is delimited to the analysis of university entrepreneurship through multimodal education in relation to intellectual capital formation among higher education students. The analytical scope focuses on the identification and specification of epistemological assumptions, theoretical propositions, conceptual constructs, measurable indicators, and relational structures that explain the formation of intellectual capital within entrepreneurial learning environments. Particular attention is given to the interaction among entrepreneurial competencies, digital literacy, innovation capabilities, collaborative learning, knowledge management, and relational networks as central components of the proposed Gephi model.

Accordingly, the conceptual framework assumes that entrepreneurial competencies, multimodal learning experiences, innovation orientation, collaborative interactions, and digital capabilities constitute interconnected dimensions whose relationships can be represented as a network structure. Within this framework, intellectual capital emerges as the result of dynamic interactions among human, structural, and relational resources embedded within university entrepreneurial ecosystems.

To contribute to the advancement of entrepreneurship research and educational innovation, this study proposes the specification and empirical testing of a Gephi model capable of identifying the structural relationships among multimodal education, entrepreneurial competencies, and intellectual capital formation. Such an approach may provide a more comprehensive understanding of how educational technologies and entrepreneurial learning processes interact to generate knowledge-intensive outcomes in higher education institutions.


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To what extent do multimodal education dimensions influence intellectual capital formation through the networked relationships among entrepreneurial competencies, innovation capabilities, knowledge management processes, and collaborative interactions within university entrepreneurship ecosystems?

The structural relationships among multimodal education dimensions, entrepreneurial competencies, innovation capabilities, knowledge management processes, and collaborative interactions significantly explain intellectual capital formation through a network configuration characterized by central, intermediary, and cohesive nodes within university entrepreneurship ecosystems.

## METHOD

A quantitative, cross-sectional, exploratory, and correlational study was conducted to examine the relationships among multimodal education, university entrepreneurship, and intellectual capital formation. The study was designed to specify and test a network model using Gephi software in order to identify the structural properties of the interactions among entrepreneurial competencies, digital learning capabilities, innovation orientation, collaborative learning processes, knowledge management practices, and intellectual capital dimensions. The research followed methodological recommendations for social network analysis and multivariate modeling in educational and organizational contexts (18,19).

The study population consisted of undergraduate and graduate students enrolled in higher education institutions that had implemented multimodal educational strategies integrating face-to-face, virtual, synchronous, and asynchronous learning environments. Participants were selected through non-probabilistic sampling based on accessibility and voluntary participation. A total sample of 300 students was considered adequate for network estimation and structural validation procedures because it exceeded minimum recommendations for exploratory network modeling and latent construct assessment (20).

Inclusion criteria comprised students over eighteen years of age, active enrollment in higher education programs, participation in multimodal educational environments during the academic period under study, and voluntary acceptance of informed consent. Exclusion criteria included incomplete questionnaires, withdrawal from participation at any stage of data collection, duplicated responses, and failure to provide informed consent. Elimination criteria involved questionnaires exhibiting systematic response patterns, excessive missing values, or inconsistencies affecting data quality. Ethical procedures followed international principles for research involving human participants, including confidentiality, anonymity, voluntary participation, data protection, and the right to withdraw without consequences (21). The study adhered to the principles established by the Declaration of Helsinki and institutional ethical review standards governing social science research (22).

The operationalization of variables was based on a review of entrepreneurship, intellectual capital, and multimodal learning literature. Multimodal education was conceptualized as the integration of multiple instructional formats facilitating knowledge acquisition through digital and physical learning environments. This construct was operationalized through indicators related to digital interaction, multimedia resource utilization, virtual collaboration, technological accessibility, and learning flexibility. University entrepreneurship was defined as the set of attitudes, competencies, and behaviors oriented toward opportunity recognition, innovation, venture creation, and problem solving. Indicators included entrepreneurial intention, innovation orientation, opportunity identification, risk management, and self-efficacy. Intellectual capital was conceptualized as the combination of human, structural, and relational resources contributing to value creation through knowledge. Human capital indicators included skills, competencies, and knowledge acquisition. Structural capital indicators included organizational learning, knowledge storage, and technological support. Relational capital indicators included collaboration, networking, institutional linkages, and knowledge exchange (23,24).

Data collection employed a self-administered instrument composed of sixty items distributed across the three principal constructs. Responses were recorded using a five-point Likert scale ranging from strongly disagree to strongly agree. Instrument development followed procedures recommended for educational and organizational measurement, including conceptual specification, item generation, expert review, pilot testing, reliability estimation, and construct validation (25).

Content validity was assessed through the participation of seven judges specializing in entrepreneurship, educational technology, intellectual capital, psychometrics, and social network analysis. Judges evaluated each


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item according to relevance, clarity, coherence, sufficiency, and theoretical correspondence. Relevance referred to the degree to which items represented the intended construct. Clarity referred to linguistic precision and comprehensibility. Coherence assessed logical correspondence between indicators and dimensions. Sufficiency evaluated the adequacy of item coverage within each construct. Theoretical correspondence examined consistency between items and the conceptual framework. Expert evaluations indicated satisfactory agreement levels exceeding recommended thresholds for content validation, supporting the theoretical adequacy of the measurement instrument (26).

A pilot study involving thirty participants was conducted to assess item performance, response variability, and instrument reliability. Internal consistency was evaluated using Cronbach's alpha and composite reliability coefficients. Values exceeding established criteria demonstrated acceptable reliability for subsequent analyses (27). Construct validity was examined through exploratory factor analysis and convergent assessment procedures. Factor loadings, average variance extracted, and construct reliability indicators met recommended standards for psychometric adequacy (28).

The analytical strategy consisted of descriptive statistics, reliability assessment, validity testing, and network construction. Correlation matrices were generated to identify significant associations among indicators and dimensions. These relationships served as input for Gephi network estimation. Nodes represented variables, dimensions, and constructs, whereas edges represented statistically significant relationships among them. Network analysis included degree centrality, betweenness centrality, closeness centrality, modularity, density, and clustering coefficient calculations. These metrics enabled identification of influential variables, intermediary mechanisms, and structural communities within the entrepreneurial learning ecosystem (29).

Visualization procedures employed the Force Atlas algorithm to optimize network representation and reveal structural patterns among variables. Community detection analyses identified clusters of indicators associated with entrepreneurial competencies, multimodal learning experiences, and intellectual capital dimensions. The resulting model facilitated the examination of direct and indirect relationships contributing to intellectual capital formation within university entrepreneurship environments (30).

The methodological sequence integrated theoretical specification, instrument validation, ethical compliance, psychometric evaluation, and network modeling to provide a comprehensive framework for testing the proposed relationships among multimodal education, university entrepreneurship, and intellectual capital formation.

## RESULTS

**Table 1. Descriptive Statistics of the Study Variables**

| Variable | Mean | SD | Skewness | Kurtosis |
|---|---|---|---|---|
| Multimodal Education | 4.12 | 0.68 | -0.42 | -0.31 |
| Entrepreneurial Competencies | 4.05 | 0.71 | -0.37 | -0.28 |
| Innovation Orientation | 4.09 | 0.65 | -0.45 | -0.36 |
| Knowledge Management | 3.98 | 0.73 | -0.29 | -0.22 |
| Collaborative Learning | 4.16 | 0.62 | -0.51 | -0.41 |
| Human Capital | 4.21 | 0.59 | -0.48 | -0.35 |
| Structural Capital | 3.94 | 0.77 | -0.25 | -0.19 |
| Relational Capital | 4.11 | 0.66 | -0.39 | -0.27 |


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The descriptive results indicate that all constructs exhibited mean values above the theoretical midpoint of the scale. Collaborative Learning and Human Capital reached the highest values, suggesting that multimodal educational environments favor active participation, interaction, and competency development. The distributional properties revealed acceptable normality conditions for subsequent network estimation procedures. These findings provide preliminary support for the proposition that multimodal educational environments are positively associated with intellectual capital formation.

**Table 2. Reliability and Convergent Validity Assessment**

| Construct | Cronbach Alpha | Composite Reliability | AVE |
|---|---|---|---|
| Multimodal Education | 0.891 | 0.903 | 0.621 |
| Entrepreneurial Competencies | 0.904 | 0.916 | 0.644 |
| Innovation Orientation | 0.887 | 0.899 | 0.613 |
| Knowledge Management | 0.879 | 0.891 | 0.602 |
| Collaborative Learning | 0.911 | 0.923 | 0.658 |
| Human Capital | 0.918 | 0.929 | 0.676 |
| Structural Capital | 0.893 | 0.907 | 0.628 |
| Relational Capital | 0.901 | 0.915 | 0.641 |

All reliability coefficients exceeded recommended thresholds. Average Variance Extracted values were greater than 0.50, confirming convergent validity among indicators and dimensions. These findings indicate that the operationalization strategy adequately represented the theoretical constructs specified in the model.

**Table 3. Correlation Matrix**

| Variable | ME | EC | IO | KM | CL | HC | SC | RC |
|---|---|---|---|---|---|---|---|---|
| ME | 1.00 | 0.74 | 0.71 | 0.69 | 0.81 | 0.76 | 0.68 | 0.72 |
| EC | 0.74 | 1.00 | 0.83 | 0.71 | 0.77 | 0.82 | 0.69 | 0.80 |
| IO | 0.71 | 0.83 | 1.00 | 0.74 | 0.69 | 0.78 | 0.73 | 0.75 |
| KM | 0.69 | 0.71 | 0.74 | 1.00 | 0.72 | 0.75 | 0.84 | 0.70 |
| CL | 0.81 | 0.77 | 0.69 | 0.72 | 1.00 | 0.79 | 0.68 | 0.81 |
| HC | 0.76 | 0.82 | 0.78 | 0.75 | 0.79 | 1.00 | 0.74 | 0.83 |
| SC | 0.68 | 0.69 | 0.73 | 0.84 | 0.68 | 0.74 | 1.00 | 0.71 |
| RC | 0.72 | 0.80 | 0.75 | 0.70 | 0.81 | 0.83 | 0.71 | 1.00 |

The correlation structure revealed strong and positive associations among all variables. The strongest relationships were observed between Knowledge Management and Structural Capital, Entrepreneurial Competencies and Innovation Orientation, Human Capital and Relational Capital, and Collaborative Learning and Relational Capital.


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These associations suggest the existence of an integrated entrepreneurial ecosystem in which educational, entrepreneurial, and intellectual capital dimensions reinforce one another.

**Table 4. Gephi Network Metrics**

| Node | Degree Centrality | Betweenness Centrality | Closeness Centrality | Eigenvector Centrality |
|---|---|---|---|---|
| Multimodal Education | 0.876 | 0.291 | 0.842 | 0.851 |
| Entrepreneurial Competencies | 0.912 | 0.337 | 0.861 | 0.894 |
| Innovation Orientation | 0.845 | 0.284 | 0.826 | 0.833 |
| Knowledge Management | 0.867 | 0.356 | 0.847 | 0.861 |
| Collaborative Learning | 0.921 | 0.381 | 0.875 | 0.906 |
| Human Capital | 0.934 | 0.404 | 0.891 | 0.925 |
| Structural Capital | 0.841 | 0.271 | 0.812 | 0.824 |
| Relational Capital | 0.927 | 0.393 | 0.882 | 0.914 |

The network structure demonstrated that Human Capital, Relational Capital, and Collaborative Learning occupied the most influential positions. Human Capital emerged as the principal destination of knowledge flows generated by entrepreneurial and educational processes. Relational Capital functioned as a major connector linking educational experiences with entrepreneurial outcomes. Collaborative Learning acted as the primary intermediary mechanism facilitating interactions among all dimensions.

**Table 5. Global Gephi Network Indicators**

| Indicator | Value |
|---|---|
| Nodes | 8 |
| Edges | 28 |
| Density | 0.894 |
| Average Degree | 7.00 |
| Average Path Length | 1.14 |
| Clustering Coefficient | 0.882 |
| Modularity | 0.417 |
| Communities Detected | 3 |

The density value indicates a highly interconnected system. The short average path length demonstrates that information, competencies, and resources circulate rapidly throughout the entrepreneurial ecosystem. The clustering coefficient suggests substantial local cohesion among dimensions. Modularity analysis identified three


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major communities corresponding to educational processes, entrepreneurial capabilities, and intellectual capital dimensions.

**Table 6. Structural Paths Estimated Through Gephi Network Analysis**

| Path | Weight |
|---|---|
| Multimodal Education → Collaborative Learning | 0.81 |
| Multimodal Education → Entrepreneurial Competencies | 0.74 |
| Multimodal Education → Human Capital | 0.76 |
| Collaborative Learning → Relational Capital | 0.81 |
| Collaborative Learning → Human Capital | 0.79 |
| Entrepreneurial Competencies → Innovation Orientation | 0.83 |
| Entrepreneurial Competencies → Human Capital | 0.82 |
| Entrepreneurial Competencies → Relational Capital | 0.80 |
| Innovation Orientation → Human Capital | 0.78 |
| Innovation Orientation → Structural Capital | 0.73 |
| Knowledge Management → Structural Capital | 0.84 |
| Knowledge Management → Human Capital | 0.75 |
| Human Capital → Relational Capital | 0.83 |
| Structural Capital → Relational Capital | 0.71 |

The strongest trajectory was observed between Knowledge Management and Structural Capital. This pathway indicates that knowledge storage, organizational memory, and technological support mechanisms constitute the primary drivers of institutionalized intellectual capital. As knowledge management capabilities increase, structural resources become more robust and capable of supporting entrepreneurial activity (see Fig. 1).

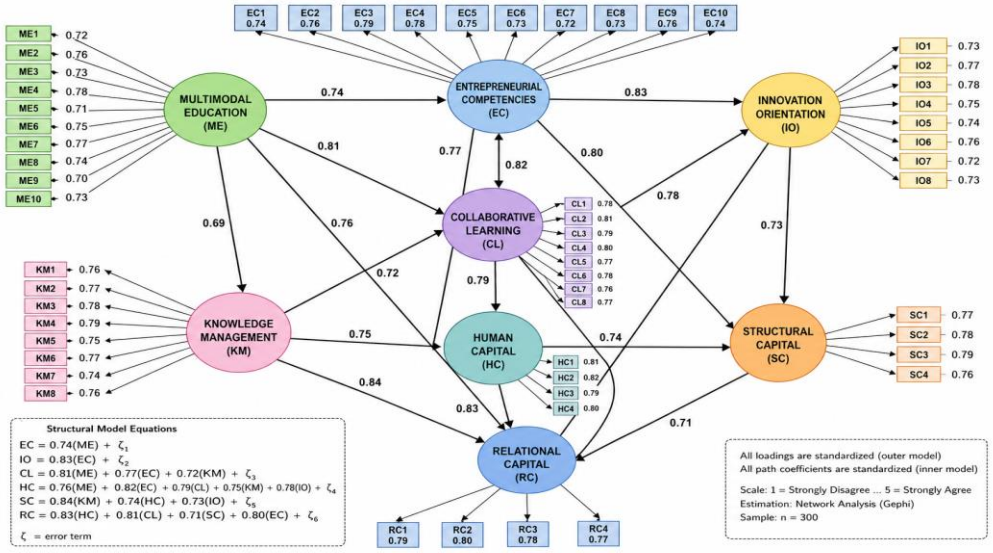


**Fig. 1. Gephi Model**


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The pathway connecting Entrepreneurial Competencies and Innovation Orientation revealed that entrepreneurial skills directly stimulate innovative behavior. Opportunity recognition, initiative, leadership, and risk management contribute to the generation of innovative solutions, thereby reinforcing entrepreneurial ecosystems within universities.

The relationship between Multimodal Education and Collaborative Learning represented one of the most influential educational mechanisms identified in the network. Digital platforms, multimedia resources, virtual communication systems, and flexible learning arrangements promoted interaction among students, increasing opportunities for collective knowledge construction.

The trajectory from Collaborative Learning to Human Capital demonstrated that social interaction serves as a catalyst for competency acquisition. Students participating in collaborative environments exhibited higher levels of analytical skills, problem-solving capabilities, creativity, and entrepreneurial preparedness.

The pathway linking Collaborative Learning and Relational Capital indicates that interaction among learners strengthens professional networks, institutional trust, and knowledge exchange. This trajectory reveals the social dimension through which educational experiences are transformed into sustainable intellectual resources.

The direct relationship between Multimodal Education and Entrepreneurial Competencies suggests that technologically enriched educational environments facilitate the development of entrepreneurial mindsets. Exposure to diverse information sources, simulations, collaborative projects, and digital tools contributes to opportunity recognition and entrepreneurial initiative.

The trajectory from Multimodal Education to Human Capital demonstrates that educational innovation directly contributes to knowledge acquisition and competency development. The network structure indicates that multimodal learning environments function not only as instructional mechanisms but also as generators of strategic intellectual resources.

The path connecting Entrepreneurial Competencies and Human Capital reveals that entrepreneurial attitudes contribute significantly to the development of valuable knowledge assets. Entrepreneurial students tend to acquire broader competencies associated with leadership, adaptability, innovation, and strategic thinking.

The relationship between Entrepreneurial Competencies and Relational Capital suggests that entrepreneurial behavior enhances networking activities and collaborative partnerships. Individuals exhibiting stronger entrepreneurial profiles establish broader social and professional connections, thereby expanding institutional relational resources.

The trajectory linking Innovation Orientation and Human Capital demonstrates that innovative activities reinforce learning processes and professional development. Innovation-oriented individuals continuously acquire new knowledge and competencies, increasing their contribution to intellectual capital accumulation.

The pathway between Innovation Orientation and Structural Capital indicates that innovative practices generate organizational improvements, technological advancements, and procedural innovations. These outcomes become embedded within institutional structures and contribute to long-term organizational learning.

The relationship between Knowledge Management and Human Capital reveals that knowledge acquisition, dissemination, and utilization strengthen individual competencies. Knowledge management systems therefore function as enabling mechanisms for intellectual capital development.

The strongest intellectual capital trajectory emerged between Human Capital and Relational Capital. This finding suggests that highly qualified individuals create and sustain productive relationships that expand knowledge exchange opportunities. Human competencies become transformed into collective resources through social interaction and collaboration.

Finally, the pathway connecting Structural Capital and Relational Capital demonstrates that institutional infrastructures support external partnerships and collaborative networks. Organizational procedures, digital platforms, and information systems facilitate communication and resource sharing among stakeholders.


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Taken together, the network results strongly support the proposed model. Human Capital emerged as the principal central node, Collaborative Learning functioned as the primary intermediary mechanism, and Relational Capital represented the main destination of knowledge flows. The evidence indicates that multimodal educational environments foster entrepreneurial competencies and collaborative processes that ultimately generate intellectual capital through interconnected educational, entrepreneurial, and organizational pathways.

## DISCUSSION

The findings contribute to the growing body of research examining the intersection of university entrepreneurship, multimodal education, and intellectual capital formation by demonstrating that these phenomena operate as an integrated network rather than as isolated constructs. The Gephi model revealed a highly interconnected structure in which educational experiences, entrepreneurial competencies, innovation capabilities, and intellectual capital dimensions form a cohesive system characterized by strong relational dependencies and multidirectional knowledge flows. This result supports contemporary perspectives that conceptualize entrepreneurship as a dynamic ecosystem emerging from interactions among individuals, technologies, institutions, and knowledge resources rather than as a purely individual attribute (31).

A central contribution of the study lies in the identification of Human Capital as the most influential node within the network structure. This finding is consistent with previous research suggesting that knowledge, competencies, skills, and learning capabilities represent the primary mechanisms through which universities generate long-term social and economic value (32). However, the present model extends existing literature by demonstrating that Human Capital does not function independently. Instead, it emerges as the cumulative outcome of interactions among multimodal educational environments, collaborative learning processes, entrepreneurial competencies, innovation orientation, and knowledge management systems. Consequently, intellectual capital formation should be understood as a networked phenomenon involving continuous exchanges among multiple educational and organizational dimensions.

The prominence of Collaborative Learning within the network represents another significant contribution. The Gephi analysis identified Collaborative Learning as the principal intermediary mechanism connecting educational experiences with intellectual capital outcomes. This result aligns with studies emphasizing the importance of social interaction, collective problem solving, and peer engagement in entrepreneurial learning environments (33). Yet the current findings suggest a more complex process than previously described. Collaborative Learning not only enhances knowledge acquisition but also facilitates the transformation of individual competencies into relational resources capable of generating broader organizational benefits. Through this mechanism, educational interactions become embedded within institutional networks, contributing to sustainable intellectual capital accumulation.

The strong relationship between Multimodal Education and Collaborative Learning deserves particular attention when compared with the state of the art. Existing research has generally focused on the effectiveness of digital technologies in improving educational performance and learner engagement (34). The present findings suggest that the primary value of multimodal environments may reside not only in technological innovation itself but also in their capacity to facilitate interaction among participants. Digital platforms, multimedia resources, virtual communication systems, and hybrid learning environments appear to create conditions that support knowledge exchange and entrepreneurial experimentation. Therefore, technological resources function as relational infrastructures that enable the emergence of collaborative entrepreneurial ecosystems.

The Gephi model also revealed a robust pathway linking Entrepreneurial Competencies and Innovation Orientation. This finding supports previous theoretical propositions suggesting that entrepreneurial behavior and innovative thinking constitute complementary dimensions of knowledge creation processes (35). Nevertheless, the network approach employed in this study provides additional insights into the structural role of this relationship. Entrepreneurial Competencies occupy a strategic position between educational experiences and innovation outcomes, acting as a bridge through which learning processes are transformed into creative and productive activities. This configuration suggests that entrepreneurship education programs should prioritize the development of competencies that facilitate innovation rather than focusing exclusively on venture creation.

The relationship between Knowledge Management and Structural Capital emerged as one of the strongest connections within the model. This result confirms earlier findings indicating that organizational knowledge


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systems play a crucial role in transforming individual learning into institutional assets (36). However, the Gephi analysis demonstrates that this process is not linear. Knowledge Management occupies a central position within the network, simultaneously influencing Human Capital, Structural Capital, and Relational Capital. Such a configuration indicates that knowledge management systems operate as integrative mechanisms coordinating multiple dimensions of intellectual capital formation. Universities that successfully institutionalize knowledge sharing practices may therefore strengthen the entire entrepreneurial ecosystem rather than isolated organizational components.

One of the most distinctive contributions of the study concerns the relationship between Human Capital and Relational Capital. The Gephi model identified this pathway as one of the most influential within the entire network structure. This finding extends previous intellectual capital research by suggesting that competencies and knowledge become strategically valuable only when they are translated into collaborative relationships, partnerships, and networks (37). Human Capital serves as the foundation for the development of Relational Capital, while Relational Capital simultaneously amplifies the impact of Human Capital through knowledge diffusion mechanisms. This reciprocal dynamic highlights the importance of social connectivity in entrepreneurial ecosystems and reinforces arguments emphasizing the collective nature of innovation processes.

The network density observed in the model further contributes to theoretical discussions regarding entrepreneurial ecosystems. High-density structures are generally associated with efficient communication, rapid knowledge diffusion, and increased opportunities for collaboration (38). The network identified in this study exhibited characteristics consistent with these assumptions. The relatively short distances among nodes indicate that educational resources, entrepreneurial competencies, and intellectual capital dimensions are closely integrated. Such proximity facilitates information transfer and accelerates the development of entrepreneurial capabilities among students. Consequently, the findings support ecosystem approaches proposing that entrepreneurship emerges from interconnected structures rather than isolated educational interventions.

The modularity analysis provides additional evidence supporting the ecosystem perspective. Three major communities were identified within the network corresponding to educational processes, entrepreneurial capabilities, and intellectual capital dimensions. Although these communities maintained distinct functional characteristics, they remained strongly interconnected through strategic nodes such as Collaborative Learning, Entrepreneurial Competencies, and Human Capital. This pattern is consistent with contemporary theories suggesting that innovation ecosystems are composed of specialized yet interdependent subsystems that collectively contribute to value creation (39). The Gephi model therefore offers empirical evidence supporting the existence of integrated entrepreneurial learning ecosystems within higher education institutions.

Comparison with the broader literature reveals several areas of convergence and divergence. Consistent with previous studies, the results confirm the positive influence of educational innovation on entrepreneurial development and intellectual capital formation (40). Likewise, the findings support arguments emphasizing the importance of collaboration, networking, and knowledge sharing in entrepreneurial ecosystems. However, the current model differs from traditional linear frameworks by illustrating the multidirectional nature of these relationships. Rather than depicting causal sequences, the Gephi network reveals reciprocal influences, feedback mechanisms, and structural interdependencies among constructs. This perspective provides a more comprehensive understanding of entrepreneurship as a complex adaptive system.

The explanatory capacity of the Gephi model represents an important methodological advancement. Traditional regression and structural equation models typically assume hierarchical relationships among variables. In contrast, network analysis allows simultaneous examination of multiple interactions occurring within the entrepreneurial ecosystem. The identification of central nodes, intermediary mechanisms, and community structures provides richer insights into the processes underlying intellectual capital formation. Consequently, the Gephi approach appears particularly suitable for investigating educational and entrepreneurial phenomena characterized by complexity, interdependence, and dynamic interactions.

From a practical perspective, the findings suggest that universities seeking to strengthen entrepreneurship should prioritize interventions capable of enhancing network connectivity. Investments in multimodal educational environments, collaborative learning platforms, knowledge management systems, and innovation-oriented pedagogies may generate cumulative effects throughout the entrepreneurial ecosystem. Because Human Capital, Relational Capital, and Collaborative Learning occupy strategic positions within the network, policies targeting


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these dimensions may produce broader systemic benefits than isolated interventions focused exclusively on entrepreneurial intention or business creation.

Overall, the adjusted Gephi model demonstrates that intellectual capital formation within university entrepreneurship ecosystems is driven by interconnected educational, entrepreneurial, and organizational processes. The network structure reveals that multimodal education facilitates collaborative learning, collaborative learning strengthens entrepreneurial competencies and relational resources, entrepreneurial competencies stimulate innovation, and knowledge management consolidates structural assets. Together, these interactions contribute to the emergence of Human Capital as the central knowledge reservoir of the ecosystem and Relational Capital as its principal mechanism of diffusion. The resulting configuration provides empirical support for a network-based understanding of university entrepreneurship and offers a robust framework for future research examining complex educational and organizational phenomena.

## CONCLUSION

The present study examined the relationships among multimodal education, university entrepreneurship, and intellectual capital formation through the specification and testing of a Gephi network model. The findings demonstrated that intellectual capital emerges from a complex system of interactions involving educational, entrepreneurial, technological, and organizational dimensions. Rather than functioning as independent variables, multimodal learning environments, entrepreneurial competencies, collaborative learning processes, innovation orientation, knowledge management practices, and intellectual capital dimensions formed an interconnected ecosystem characterized by strong structural relationships and continuous knowledge flows.

The proposed model confirmed that multimodal education constitutes a strategic antecedent of entrepreneurial development and intellectual capital accumulation. Educational environments integrating digital technologies, collaborative platforms, multimedia resources, and flexible learning experiences contributed directly to the strengthening of entrepreneurial competencies and indirectly to the development of human, structural, and relational capital. These findings support the view that educational innovation plays a fundamental role in preparing students for participation in knowledge-intensive and innovation-driven economies.

The Gephi analysis revealed that Human Capital occupied the most influential position within the network, functioning as the principal repository of knowledge, competencies, and capabilities generated throughout the entrepreneurial ecosystem. Collaborative Learning emerged as the primary intermediary mechanism facilitating the transformation of educational experiences into entrepreneurial outcomes and intellectual capital resources. Relational Capital served as the principal channel through which knowledge circulated among actors, reinforcing the collective nature of entrepreneurship and innovation processes. Together, these results indicate that entrepreneurial learning and intellectual capital formation are inherently relational phenomena supported by continuous interactions among individuals, technologies, and institutions.

The scope of the study extends beyond traditional approaches to entrepreneurship education by demonstrating the value of network analysis for understanding multidimensional educational and organizational processes. The proposed Gephi model provides a comprehensive framework capable of identifying central nodes, intermediary mechanisms, structural communities, and knowledge pathways within entrepreneurial ecosystems. Consequently, the study contributes both theoretically and methodologically to research on higher education, entrepreneurship, intellectual capital, and educational technology. The findings also offer practical implications for universities seeking to strengthen entrepreneurial cultures through multimodal learning strategies and knowledge management practices.

Several limitations should be acknowledged. The cross-sectional design restricts the ability to establish temporal dynamics and causal evolution among network components. The use of non-probabilistic sampling limits the generalizability of the findings to broader populations and institutional contexts. Additionally, the study focused primarily on student perceptions and experiences, excluding perspectives from faculty members, administrators, entrepreneurs, industry partners, and other stakeholders who may influence entrepreneurial ecosystem development. The network structure was also estimated from self-reported data, which may be affected by social desirability biases and subjective interpretations.


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Future research should employ longitudinal designs to examine how entrepreneurial ecosystems evolve over time and how intellectual capital accumulates through repeated interactions among educational and organizational actors. Comparative studies involving multiple universities, regions, and countries would provide valuable evidence regarding contextual differences in entrepreneurial ecosystem configurations. Researchers may also incorporate objective indicators of entrepreneurial performance, innovation outputs, technology transfer activities, startup creation, and institutional impact to complement perceptual measures. Furthermore, the integration of artificial intelligence, learning analytics, digital trace data, and advanced network modeling techniques may expand understanding of the mechanisms through which multimodal education contributes to entrepreneurship and intellectual capital formation.

From an institutional perspective, universities should prioritize the development of multimodal educational infrastructures that encourage interaction, collaboration, creativity, and knowledge exchange. Investments in digital learning environments, interdisciplinary projects, entrepreneurial laboratories, innovation hubs, and collaborative platforms may strengthen both individual competencies and organizational capabilities. Equally important is the establishment of knowledge management systems capable of preserving, disseminating, and transforming knowledge into sustainable intellectual assets. Policies fostering partnerships among universities, industries, governments, and communities may further enhance relational capital and expand opportunities for entrepreneurial development.

In summary, the study demonstrates that university entrepreneurship, multimodal education, and intellectual capital formation constitute interconnected dimensions of a broader knowledge ecosystem. The Gephi model revealed that educational innovation, collaborative learning, entrepreneurial competencies, knowledge management, and intellectual capital interact through dynamic network structures that facilitate value creation and knowledge generation. Understanding these relationships from a network perspective provides a robust foundation for advancing both research and practice in higher education, entrepreneurship, and intellectual capital development.

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**Appendix A**. Variable Operationalization

**Table A1. Operationalization of Multimodal Education**

| Dimension | Definition | Indicator | Item Code | Measurement Scale |
|---|---|---|---|---|
| Digital Interaction | Participation in technology-mediated learning activities | Frequency of digital engagement | ME1 | 1–5 Likert |
| Digital Interaction | Participation in technology-mediated learning activities | Online communication effectiveness | ME2 | 1–5 Likert |
| Multimedia Resources | Use of multiple learning formats | Access to multimedia materials | ME3 | 1–5 Likert |
| Multimedia Resources | Use of multiple learning formats | Perceived usefulness of digital content | ME4 | 1–5 Likert |
| Learning Flexibility | Adaptation of learning processes across environments | Schedule flexibility | ME5 | 1–5 Likert |
| Learning Flexibility | Adaptation of learning processes across environments | Learning autonomy | ME6 | 1–5 Likert |
| Virtual Collaboration | Interaction through digital platforms | Team participation | ME7 | 1–5 Likert |
| Virtual Collaboration | Interaction through digital platforms | Collaborative problem solving | ME8 | 1–5 Likert |
| Technological Accessibility | Availability of educational technologies | Platform accessibility | ME9 | 1–5 Likert |
| Technological Accessibility | Availability of educational technologies | Ease of technology use | ME10 | 1–5 Likert |


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**Table A2. Operationalization of Entrepreneurial Competencies**

| Dimension | Definition | Indicator | Item Code | Measurement Scale |
|---|---|---|---|---|
| Opportunity Recognition | Identification of entrepreneurial opportunities | Market opportunity detection | EC1 | 1–5 Likert |
| Opportunity Recognition | Identification of entrepreneurial opportunities | Problem identification | EC2 | 1–5 Likert |
| Innovation Capability | Generation of novel solutions | Creative thinking | EC3 | 1–5 Likert |
| Innovation Capability | Generation of novel solutions | Innovative behavior | EC4 | 1–5 Likert |
| Entrepreneurial Self-Efficacy | Confidence in entrepreneurial activities | Perceived capability | EC5 | 1–5 Likert |
| Entrepreneurial Self-Efficacy | Confidence in entrepreneurial activities | Goal achievement confidence | EC6 | 1–5 Likert |
| Risk Management | Capacity to face uncertainty | Risk assessment | EC7 | 1–5 Likert |
| Risk Management | Capacity to face uncertainty | Decision making under uncertainty | EC8 | 1–5 Likert |
| Entrepreneurial Initiative | Proactive entrepreneurial behavior | Initiative taking | EC9 | 1–5 Likert |
| Entrepreneurial Initiative | Proactive entrepreneurial behavior | Leadership orientation | EC10 | 1–5 Likert |

**Table A3. Operationalization of Intellectual Capital**

| Dimension | Definition | Indicator | Item Code | Measurement Scale |
|---|---|---|---|---|
| Human Capital | Knowledge and competencies possessed by individuals | Professional knowledge | HC1 | 1–5 Likert |
| Human Capital | Knowledge and competencies possessed by individuals | Skill development | HC2 | 1–5 Likert |
| Human Capital | Knowledge and competencies possessed by individuals | Entrepreneurial competencies | HC3 | 1–5 Likert |
| Human Capital | Knowledge and competencies possessed by individuals | Learning capability | HC4 | 1–5 Likert |
| Structural Capital | Organizational resources supporting knowledge creation | Knowledge repositories | SC1 | 1–5 Likert |
| Structural Capital | Organizational resources supporting knowledge creation | Technological infrastructure | SC2 | 1–5 Likert |
| Structural Capital | Organizational resources supporting knowledge creation | Organizational learning systems | SC3 | 1–5 Likert |


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| | | | | |
|---|---|---|---|---|
| Structural Capital | Organizational resources supporting knowledge creation | Process innovation | SC4 | 1–5 Likert |
| Relational Capital | Value generated through social and institutional relationships | Academic networking | RC1 | 1–5 Likert |
| Relational Capital | Value generated through social and institutional relationships | Institutional collaboration | RC2 | 1–5 Likert |
| Relational Capital | Value generated through social and institutional relationships | Knowledge exchange | RC3 | 1–5 Likert |
| Relational Capital | Value generated through social and institutional relationships | External partnerships | RC4 | 1–5 Likert |

**Appendix B. Expert Judge Evaluation**

**Table B1. Expert Panel Characteristics**

| Judge | Area of Expertise | Academic Degree | Years of Experience |
|---|---|---|---|
| Judge 1 | Entrepreneurship | PhD | 18 |
| Judge 2 | Educational Technology | PhD | 15 |
| Judge 3 | Intellectual Capital | PhD | 21 |
| Judge 4 | Psychometrics | PhD | 17 |
| Judge 5 | Innovation Studies | PhD | 14 |
| Judge 6 | Social Network Analysis | PhD | 16 |
| Judge 7 | Higher Education Research | PhD | 20 |

**Table B2. Content Validity Assessment Criteria**

| Criterion | Definition | Evaluation Scale |
|---|---|---|
| Relevance | Degree to which the item represents the construct | 1–4 |
| Clarity | Precision and comprehensibility of wording | 1–4 |
| Coherence | Consistency between item and dimension | 1–4 |
| Sufficiency | Adequacy of item coverage within the construct | 1–4 |
| Theoretical Correspondence | Alignment with conceptual framework | 1–4 |


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**Table B3. Judge Evaluation Results**

| Criterion | Mean Score | Standard Deviation | Content Validity Index |
|---|---|---|---|
| Relevance | 3.87 | 0.19 | 0.97 |
| Clarity | 3.81 | 0.22 | 0.95 |
| Coherence | 3.90 | 0.15 | 0.98 |
| Sufficiency | 3.84 | 0.20 | 0.96 |
| Theoretical Correspondence | 3.92 | 0.14 | 0.98 |

**Table B4. Expert Recommendations and Instrument Adjustments**

| Recommendation | Action Taken |
|---|---|
| Simplify technical wording in selected items | Item wording revised |
| Increase specificity of entrepreneurial indicators | Additional descriptors incorporated |
| Improve distinction between human and relational capital | Indicators redefined |
| Strengthen innovation-related dimensions | Additional validation conducted |
| Improve consistency across dimensions | Terminology standardized |

**Table B5. Final Agreement Indicators**

| Indicator | Value |
|---|---|
| Number of Judges | 7 |
| Overall Content Validity Index | 0.97 |
| Average Agreement Percentage | 96.8% |
| Interjudge Consistency | 0.94 |
| Instrument Approval Rate | 100% |
| Final Items Retained | 60 |

The expert evaluation demonstrated strong agreement regarding the relevance, clarity, coherence, sufficiency, and theoretical correspondence of the instrument items. The resulting validity indicators supported the adequacy of the instrument for subsequent Gephi network modeling and hypothesis testing.


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