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Evaluating the Effect of Human Capital on Startup Scalability Using Random Forest Regression and Variable Importance Analysis

ABSTRACT

The objective of this study was to evaluate the effect of multidimensional human capital components on startup scalability by applying Random Forest regression modeling and variable importance analysis within the startup ecosystem of Tehran. This applied quantitative study employed a cross-sectional explanatory–predictive design. The statistical population consisted of technology-oriented startups operating in Tehran, from which 214 startups were selected through purposive sampling based on operational maturity and measurable growth indicators. Data were collected using a structured questionnaire measuring human capital dimensions including innovation competence, technical expertise, managerial capability, learning orientation, workforce skill intensity, professional experience, entrepreneurial experience, team diversity, and educational background, alongside scalability indicators such as market expansion capability, operational flexibility, and scalable business model readiness. Content validity was confirmed through expert review, and reliability indices exceeded acceptable thresholds. Data analysis was conducted using Random Forest regression to model nonlinear relationships between predictors and scalability outcomes. Model performance was evaluated using cross-validation procedures, prediction accuracy metrics, and error estimation, while variable importance and partial dependence analyses were employed to identify the relative contribution and marginal effects of human capital factors. Results demonstrated strong predictive performance of the Random Forest model, explaining a substantial proportion of variance in startup scalability. Innovation competence emerged as the most influential predictor, followed by technical expertise, managerial capability, learning orientation, and workforce skill intensity. Human capital variables collectively showed significant nonlinear and interaction effects on scalability outcomes. Practical competencies and experiential knowledge exerted stronger predictive power than formal education level. Partial dependence analysis indicated threshold effects whereby increases in innovation and managerial capability significantly accelerated scalability after moderate competency levels were reached, confirming the multidimensional and synergistic nature of human capital influences on startup growth potential. The findings indicate that startup scalability is primarily driven by dynamic human capital configurations integrating innovation capacity, technical knowledge, managerial leadership, and organizational learning capability. Machine learning analysis demonstrates that scalable growth emerges from complex interactions among human competencies rather than isolated factors, highlighting the necessity of human-centered entrepreneurial strategies and talent development policies to enhance sustainable startup expansion.

Keywords: Human capital, startup scalability, Random Forest regression, machine learning, entrepreneurship, variable importance analysis, innovation competence, startup growth.

Introduction

In recent decades, startups have emerged as central engines of innovation, economic dynamism, and technological transformation across both developed and emerging economies. Unlike traditional firms, startups operate under conditions

of extreme uncertainty, rapid experimentation, and accelerated growth expectations, which collectively make scalability a defining feature of entrepreneurial success. Scalability refers not merely to organizational growth but to the capability of expanding operations, markets, and value creation without proportional increases in cost structures. Contemporary entrepreneurship research increasingly emphasizes that scalability is fundamentally shaped by intangible organizational assets rather than physical capital alone, with human capital occupying a pivotal role in determining startup survival, growth trajectories, and long-term competitiveness [1, 2].

The transition from early-stage venture formation to scalable enterprise development depends heavily on founders' competencies, team capabilities, and organizational learning processes. Human capital encompasses accumulated knowledge, skills, experience, cognitive diversity, and managerial expertise embedded within entrepreneurial teams. Founders' prior professional experience and domain expertise influence opportunity recognition, strategic decision-making, and the ability to mobilize resources under uncertainty [3, 4]. Startups characterized by strong human capital structures demonstrate greater adaptability to market shocks, faster innovation cycles, and improved access to investment networks. At the same time, research suggests that human capital effects are multidimensional and nonlinear, requiring analytical approaches capable of capturing complex interactions between individual attributes and organizational outcomes [5, 6].

Entrepreneurial ecosystems further reinforce the strategic importance of human capital. Regional innovation systems, universities, accelerators, venture capital institutions, and collaborative knowledge networks create environments where entrepreneurial talent becomes the primary driver of value creation. The integration of knowledge and business ecosystems enables startups to transform technical expertise into commercial innovation and scalable business models [7, 8]. Policy initiatives supporting innovative startups increasingly recognize that investment in human capabilities—education, mentoring, leadership development, and skill acquisition—generates stronger economic returns than traditional financial subsidies alone [1].

Human capital influences scalability through several mechanisms. First, entrepreneurial leadership shapes organizational vision, strategic alignment, and innovation orientation. Leadership competencies determine how effectively startups navigate resource constraints, technological uncertainty, and competitive pressures [9, 10]. Second, team composition and diversity affect knowledge recombination and creative problem-solving capacity. Functional diversity can accelerate growth by integrating complementary expertise; however, excessive heterogeneity may introduce coordination challenges and conflict, highlighting the dual nature of diversity within entrepreneurial teams [11, 12]. Third, talent acquisition strategies influence organizational learning speed and innovation performance, particularly in technology startups where skilled human resources represent the primary production factor [13, 14].

Beyond internal organizational characteristics, investor behavior also reflects the centrality of human capital in startup evaluation. Venture capitalists frequently assess founder competence, technical expertise, and managerial credibility as signals of growth potential and investment quality [15, 16]. Empirical studies demonstrate that entrepreneurial background, prior achievements, and professional networks strongly influence access to financing and achievement of investment milestones [17, 18]. Moreover, venture capital involvement extends beyond financial resources by providing strategic mentoring, governance expertise, and market access that amplify human capital advantages [19].

Despite growing recognition of human capital's importance, startup failure rates remain high worldwide, often linked to managerial inexperience, weak strategic coordination, or inability to scale operational processes effectively. Narrative

analyses of failed startups highlight deficiencies in team capability alignment, inadequate learning systems, and insufficient strategic leadership as recurring causes of organizational collapse [20]. Operational management capabilities also play a decisive role, as scalable startups must simultaneously optimize processes, maintain innovation agility, and manage increasing organizational complexity [21]. These findings suggest that scalability cannot be explained solely through financial resources or technological innovation but must be understood as an emergent outcome of human capital configurations.

The rapid digitalization of global economies has intensified the relevance of human capital for startup scalability. Digital platforms, artificial intelligence, and data-driven business models require interdisciplinary teams capable of integrating technological expertise with entrepreneurial strategy. Academic entrepreneurship and technology commercialization processes illustrate how specialized knowledge becomes transformed into scalable ventures when supported by entrepreneurial competencies and institutional collaboration [22, 23]. Simultaneously, geopolitical technological competition and digital transformation reshape entrepreneurial opportunities and resource access, making adaptive human capital increasingly essential for sustainable growth [24].

Startup growth also depends on institutional and lifecycle dynamics. Financial requirements, funding strategies, and growth stages shape how startups leverage human capital resources over time. Early-stage ventures rely heavily on founders' skills and social capital, while later stages require professional management structures and organizational specialization [25, 26]. Access to accelerators and structured entrepreneurial programs further enhances human capital development by providing mentorship, training, and strategic guidance that improve venture performance [27, 28]. Accelerator leadership characteristics themselves influence startup outcomes, demonstrating that human capital effects extend beyond firms to ecosystem-level actors [5].

Another emerging perspective emphasizes spatial and contextual influences on entrepreneurship. Regional ecosystems differ significantly in institutional support, innovation culture, and talent availability, shaping startup scalability potential across geographic environments [29]. Entrepreneurial success therefore results from interactions between individual competencies and environmental opportunities. Research on resource mobilization underscores that startups must combine human capital with social and organizational capital to achieve sustainable scaling trajectories [30, 31]. Furthermore, gender norms and labor market perceptions influence talent attraction and organizational development within technology startups, illustrating the social embeddedness of human capital dynamics [32].

Commercialization processes represent another domain where human capital plays a decisive role. Transforming scientific discoveries into market-ready innovations requires entrepreneurial competencies that bridge technical knowledge and business strategy [33]. Founders capable of integrating research expertise with commercialization skills demonstrate higher probabilities of scaling successfully in competitive markets. Similarly, acquisition outcomes and exit opportunities are strongly associated with organizational capabilities and leadership quality rather than technological assets alone [34]. These insights reinforce the argument that human capital constitutes a strategic asset underpinning long-term startup valuation and growth sustainability.

Although prior research provides valuable theoretical insights, methodological limitations persist in assessing the impact of human capital on scalability. Many studies rely on linear statistical models that fail to capture nonlinear relationships, interaction effects, and complex dependencies among entrepreneurial variables. The increasing availability of entrepreneurial data and advances in machine learning provide new opportunities to overcome these limitations. Machine

learning approaches enable predictive modeling capable of identifying hidden patterns and estimating variable importance within high-dimensional startup datasets [35]. Such techniques are particularly suitable for entrepreneurship research, where outcomes emerge from multiple interacting factors rather than isolated determinants.

Recent scholarship calls for integrating data-driven analytical methods with entrepreneurship theory to better understand how human capital dimensions jointly influence growth outcomes. Studies examining startup survival, innovation success, and investment attraction highlight the necessity of multidimensional modeling frameworks capable of evaluating diverse human capital attributes simultaneously [28, 36]. Additionally, contemporary entrepreneurial strategy research emphasizes sustainable capital flows, venture dynamics, and leadership capabilities as interconnected drivers of scalable entrepreneurship [9, 10]. These developments suggest that combining machine learning with human capital theory can provide deeper explanatory and predictive insights into startup scalability.

Furthermore, evolving entrepreneurial labor markets emphasize knowledge intensity, continuous learning, and innovation capability as essential determinants of competitive advantage. Strategic human resource practices increasingly function as innovation enablers rather than administrative functions, particularly within early-stage ventures where organizational flexibility and learning speed are critical [13]. Human capital analytics allow startups to systematically evaluate workforce capabilities and align talent strategies with growth objectives, reinforcing the connection between human resource management and scalable performance outcomes [6]. Consequently, investigating human capital through advanced analytical approaches contributes both theoretically and practically to entrepreneurship research.

Despite extensive literature addressing startup growth and entrepreneurial success, a comprehensive empirical examination linking multidimensional human capital indicators to scalability using machine learning techniques remains limited, particularly within emerging startup ecosystems. Addressing this gap is essential for understanding how entrepreneurial competencies translate into scalable organizational performance and for informing policy, investment, and managerial decision-making.

Therefore, the aim of this study is to evaluate the effect of human capital on startup scalability using Random Forest regression and variable importance analysis.

Methodology

This study was conducted using a quantitative applied research design with an explanatory–predictive approach aimed at modeling the relationship between human capital characteristics and startup scalability outcomes. The research employed a cross-sectional analytical framework integrating machine learning techniques with empirical startup data. The statistical population consisted of technology-based and innovative startups operating within the entrepreneurial ecosystem of Tehran, Iran. Startups were identified through official innovation centers, technology parks, startup accelerators, and registered entrepreneurial networks affiliated with Tehran’s innovation infrastructure. Inclusion criteria required startups to have completed at least two years of operational activity, possess a defined organizational structure, and demonstrate measurable growth indicators such as revenue expansion, customer acquisition, or market penetration. After preliminary screening, 214 startups met eligibility requirements and agreed to participate in the research. Within each startup, founders, senior managers, or human resource decision-makers served as key informants because of their comprehensive knowledge regarding organizational human capital and strategic development processes. The sampling procedure followed a purposive

stratified approach to ensure representation across sectors including information technology, digital platforms, fintech, e-commerce, health technology, and creative industries. The final dataset therefore represents a heterogeneous yet ecosystem-consistent sample reflecting the structural diversity of Tehran's startup environment.

Data collection was carried out using a structured multi-section research instrument developed based on theoretical models of human capital and entrepreneurial scalability. The questionnaire combined validated measurement scales with contextual indicators adapted to startup environments. Human capital variables included founders' educational attainment, professional experience, entrepreneurial experience, technical expertise, managerial capability, innovation competence, learning orientation, team diversity, and workforce skill intensity. Organizational scalability indicators were operationalized through measurable growth dimensions such as scalability readiness, operational flexibility, technological adaptability, revenue growth potential, scalability of business models, market expansion capability, and investment attractiveness. Items were measured using five-point Likert-type scales ranging from very low to very high, allowing quantitative comparison across firms. Prior to large-scale data collection, the instrument underwent expert validation by entrepreneurship scholars and startup ecosystem specialists to ensure content validity and contextual relevance. A pilot study involving 30 startups was conducted to examine clarity, reliability, and measurement stability, leading to minor wording adjustments. Reliability analysis demonstrated acceptable internal consistency coefficients exceeding recommended thresholds. Data were collected through a combination of online survey distribution and supervised completion sessions conducted with startup managers to minimize missing data and enhance response accuracy. Supplementary organizational information such as firm age, team size, funding stage, and industry classification was also gathered to support predictive modeling and control for structural differences between startups.

Data analysis was performed using advanced machine learning techniques centered on Random Forest regression modeling to examine nonlinear relationships between human capital dimensions and startup scalability. After data cleaning, missing value treatment, and normalization procedures, exploratory statistical analysis was conducted to evaluate distributions, detect outliers, and verify data integrity. Random Forest regression was selected due to its robustness against multicollinearity, capacity to capture complex interaction effects, and strong predictive performance in high-dimensional entrepreneurial datasets. The algorithm was implemented using an ensemble learning framework consisting of multiple decision trees generated through bootstrap aggregation. Model training involved repeated random sampling and cross-validation procedures to prevent overfitting and ensure generalizability of results. Hyperparameters such as the number of trees, maximum tree depth, and minimum node size were optimized through iterative tuning to maximize prediction accuracy and minimize mean squared error.

A central analytical component of the study involved variable importance analysis derived from the Random Forest model. Both Mean Decrease in Impurity and permutation-based importance metrics were calculated to determine the relative contribution of each human capital variable to startup scalability outcomes. This approach enabled identification of the most influential human capital dimensions driving scalable growth while accounting for nonlinear dependencies among predictors. Partial dependence analysis was additionally employed to visualize marginal effects of key variables and interpret how changes in human capital characteristics influence predicted scalability levels. Model performance was evaluated using multiple indicators including coefficient of determination, root mean square error, and out-of-sample prediction accuracy. All analyses were conducted using Python statistical libraries and machine learning frameworks, ensuring computational

reproducibility and methodological transparency. The integration of predictive analytics with interpretive variable importance techniques allowed the study not only to forecast scalability potential but also to generate theoretically meaningful insights regarding the strategic role of human capital in startup development within Tehran's entrepreneurial ecosystem.

Findings and Results

The findings of the study are presented in several stages, beginning with descriptive characteristics of participating startups and respondents, followed by analytical results derived from Random Forest regression modeling and variable importance analysis. A total of 214 startups located in Tehran participated in the research. Examination of demographic characteristics indicated that 62.6% of respondents were founders or co-founders, 24.8% were senior executives, and 12.6% held human resource or operational management roles. Regarding educational background, 71.5% of respondents possessed postgraduate degrees, reflecting the knowledge-intensive nature of Tehran's startup ecosystem, while 24.3% held undergraduate degrees and 4.2% reported specialized technical certifications. In terms of industry distribution, information technology and digital platform startups constituted the largest proportion of the sample (38.8%), followed by fintech (17.3%), e-commerce (15.9%), health technology (11.2%), creative industries (9.3%), and other innovation-based sectors (7.5%). Firm age analysis showed that 41.6% of startups had operated between two and four years, 36.4% between five and seven years, and 22.0% exceeded seven years of operation. Workforce size varied considerably, with early-stage teams employing fewer than ten members representing 29.4% of the sample, medium-scale startups with 10–30 employees accounting for 46.7%, and growth-stage startups exceeding 30 employees comprising 23.9%. Funding status indicated that 35.0% had received seed investment, 40.7% were in Series A or equivalent growth phases, and 24.3% were bootstrapped organizations. Overall, the demographic profile confirms that the sample represents active, growth-oriented startups suitable for examining scalability dynamics.

Table 1

Descriptive Statistics of Human Capital and Startup Scalability Variables

Variable	Mean	Standard Deviation	Minimum	Maximum
Founders' Educational Level	4.21	0.73	2.00	5.00
Professional Experience	3.98	0.81	1.00	5.00
Entrepreneurial Experience	3.74	0.89	1.00	5.00
Technical Expertise	4.35	0.66	2.00	5.00
Managerial Capability	4.02	0.77	2.00	5.00
Team Diversity	3.69	0.84	1.00	5.00
Learning Orientation	4.28	0.62	2.00	5.00
Innovation Competence	4.31	0.64	2.00	5.00
Workforce Skill Intensity	4.17	0.71	2.00	5.00
Operational Flexibility	3.95	0.78	1.00	5.00
Market Expansion Capability	4.08	0.70	2.00	5.00
Business Model Scalability	4.11	0.69	2.00	5.00
Revenue Growth Potential	4.06	0.74	1.00	5.00

The descriptive statistics presented in Table 1 indicate that human capital variables generally exhibited high mean values, demonstrating strong human resource capacity among Tehran-based startups. Technical expertise, innovation competence, and learning orientation recorded the highest averages, suggesting that startups prioritize knowledge acquisition, innovation capability, and continuous learning as core drivers of growth. Entrepreneurial experience and team diversity showed

comparatively lower means and greater dispersion, indicating variability across startups in accumulated entrepreneurial exposure and team composition. Scalability-related indicators also displayed favorable averages, particularly business model scalability and market expansion capability, reflecting growth readiness among participating firms. Standard deviation values remained within acceptable ranges, confirming sufficient variability for predictive modeling while avoiding extreme dispersion that might distort machine learning estimation.

Table 2

Random Forest Model Performance Indicators

Performance Indicator	Value
R^2 (Coefficient of Determination)	0.78
Root Mean Square Error (RMSE)	0.41
Mean Absolute Error (MAE)	0.32
Cross-Validation Accuracy	0.81
Out-of-Sample Prediction Accuracy	0.79

Results reported in Table 2 demonstrate strong predictive performance of the Random Forest regression model in estimating startup scalability. The coefficient of determination indicates that approximately 78% of the variance in scalability outcomes was explained by human capital variables included in the model. Low RMSE and MAE values confirm minimal prediction error and high model precision. Cross-validation accuracy exceeding 0.80 further validates model stability across repeated sampling iterations, while out-of-sample accuracy indicates satisfactory generalization beyond training data. These findings confirm the suitability of machine learning approaches for modeling complex entrepreneurial phenomena characterized by nonlinear interactions and multidimensional predictors.

Table 3

Variable Importance Based on Mean Decrease in Impurity

Human Capital Variable	Importance Score
Innovation Competence	0.168
Technical Expertise	0.152
Managerial Capability	0.141
Learning Orientation	0.134
Workforce Skill Intensity	0.118
Professional Experience	0.101
Entrepreneurial Experience	0.089
Team Diversity	0.061
Educational Level	0.036

The variable importance analysis presented in Table 3 reveals that innovation competence emerged as the most influential predictor of startup scalability. This finding indicates that the ability to generate and implement innovative solutions plays a decisive role in enabling scalable growth trajectories. Technical expertise and managerial capability ranked immediately after innovation competence, highlighting the complementary interaction between technical knowledge and strategic leadership in expanding startup operations. Learning orientation and workforce skill intensity also contributed substantially, emphasizing the importance of adaptive organizational learning and highly skilled human resources. In contrast, educational level demonstrated comparatively lower importance, suggesting that practical competencies and experiential capabilities exert stronger influence on scalability outcomes than formal education alone.

Table 4

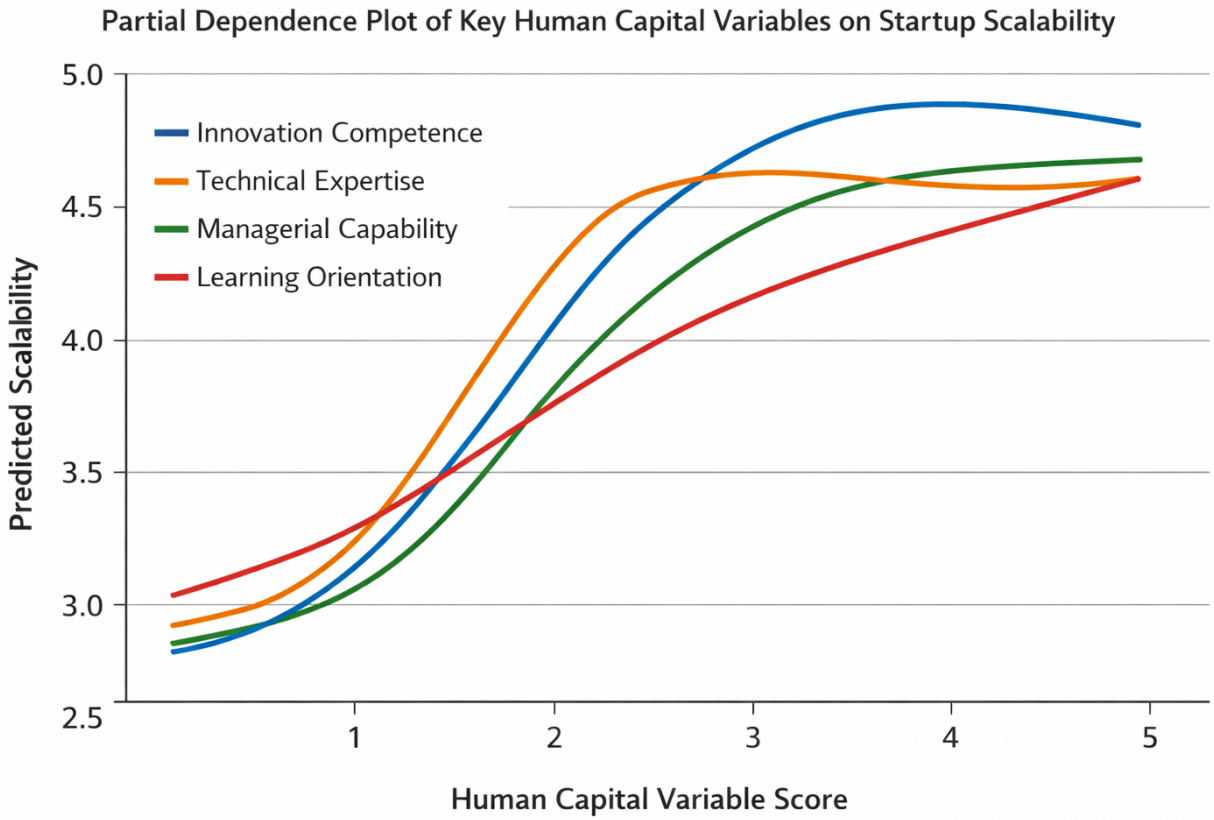
Permutation-Based Variable Importance Analysis

Human Capital Variable	Permutation Importance
Innovation Competence	0.172
Technical Expertise	0.158
Managerial Capability	0.147
Learning Orientation	0.139
Workforce Skill Intensity	0.121
Professional Experience	0.104
Entrepreneurial Experience	0.092
Team Diversity	0.067
Educational Level	0.041

Permutation importance results reported in Table 4 confirm the robustness of findings obtained from impurity-based metrics. Innovation competence consistently maintained the highest contribution to predictive accuracy, indicating that removing this variable substantially reduces model performance. Technical expertise and managerial capability again emerged as dominant predictors, reinforcing the centrality of competence-based human capital rather than purely demographic characteristics. The convergence between two independent importance estimation methods strengthens confidence in the reliability of variable ranking and demonstrates methodological consistency within the Random Forest framework.

Figure 1

Partial Dependence Plot of Key Human Capital Variables on Startup Scalability



Analysis associated with Figure 1 illustrates the nonlinear marginal effects of major human capital variables on predicted scalability levels. The partial dependence visualization shows that increases in innovation competence and technical expertise produce steep improvements in scalability predictions during early developmental stages, followed by gradual stabilization at higher levels of capability. Managerial capability demonstrates a threshold effect, whereby scalability accelerates significantly once managerial competence surpasses moderate levels. Learning orientation exhibits a steady positive relationship across all values, suggesting continuous benefits from organizational learning practices. The figure collectively indicates that startup scalability is not driven by isolated factors but rather emerges from synergistic interactions among innovation capacity, technical mastery, managerial effectiveness, and adaptive learning culture. These patterns validate the theoretical proposition that scalable startups depend on dynamic human capital configurations capable of sustaining growth under uncertain and rapidly evolving market conditions.

Discussion and Conclusion

The present study aimed to evaluate the effect of human capital on startup scalability using Random Forest regression and variable importance analysis. The findings demonstrate that human capital dimensions explain a substantial proportion of variance in startup scalability, confirming that growth potential in entrepreneurial ventures is fundamentally driven by knowledge-based and capability-oriented resources rather than purely financial or technological assets. The predictive model revealed strong explanatory power, indicating that scalability emerges as a multidimensional outcome shaped by interacting human competencies. These results reinforce contemporary entrepreneurship theory emphasizing the centrality of human capital as a strategic determinant of venture development and innovation-driven expansion [1, 2].

One of the most important findings of the study is the dominant role of innovation competence as the strongest predictor of scalability. Startups characterized by high innovation capability demonstrated significantly higher predicted scalability scores, suggesting that the capacity to continuously generate, adapt, and commercialize new ideas functions as the primary engine of sustainable growth. This result aligns with research arguing that startups create new knowledge and disruptive innovation through the cognitive and creative capabilities of entrepreneurial teams rather than through static technological advantages [2]. Studies on entrepreneurial leadership and spatial innovation similarly emphasize that innovative thinking enables startups to transform market uncertainty into growth opportunities, thereby strengthening competitive positioning [9, 10]. The findings therefore support the argument that innovation competence represents a dynamic human capital resource enabling scalable business models.

Technical expertise emerged as another highly influential factor affecting scalability. The analysis indicates that technological proficiency enhances operational efficiency, accelerates product development cycles, and improves adaptability to evolving digital markets. This observation corresponds with evidence demonstrating that technology-oriented human capital significantly influences startup survival and expansion, particularly in knowledge-intensive sectors [22, 23]. The increasing digitalization of entrepreneurship also requires interdisciplinary technical competencies capable of integrating software development, data analytics, and platform innovation. Research on investment decision-making shows that investors frequently evaluate technical expertise as a signal of venture quality and growth potential, further validating the importance of technological human capital identified in this study [15, 18].

Managerial capability was identified as a critical driver of scalability, highlighting the importance of leadership competence in coordinating organizational growth. As startups transition from early experimentation toward expansion phases, managerial skills become essential for structuring operations, managing teams, and maintaining strategic coherence. Prior studies demonstrate that founders' previous work experience and governance capability significantly influence startup growth trajectories, either facilitating rapid scaling or creating structural constraints when managerial competence is insufficient [3, 4]. Operational management research similarly confirms that scalable ventures require coordinated processes capable of sustaining efficiency while preserving innovation flexibility [21]. The present findings therefore reinforce the view that managerial human capital acts as a bridge between entrepreneurial vision and organizational execution.

Learning orientation also showed strong importance within the predictive model, indicating that startups capable of continuous knowledge acquisition and adaptation achieve superior scalability outcomes. Learning-oriented organizations respond more effectively to environmental uncertainty and technological disruption, enabling iterative improvement of products, strategies, and business models. This result is consistent with studies emphasizing organizational learning as a prerequisite for entrepreneurial resilience and long-term competitiveness [7, 8]. Accelerator programs and mentorship initiatives further strengthen learning processes by transferring experiential knowledge and managerial expertise to startup teams, thereby improving venture performance [27, 28]. Consequently, scalability should be interpreted not as a single growth event but as an adaptive learning process driven by evolving human capital.

Workforce skill intensity and professional experience were also meaningful contributors to scalability. These findings suggest that accumulated expertise and specialized workforce capabilities enhance startups' ability to manage complex tasks and pursue market expansion strategies. Human capital analytics research indicates that skilled teams contribute directly to venture performance through improved decision-making quality and operational effectiveness [6]. Entrepreneurial background studies similarly demonstrate that founders' prior experiences increase credibility, facilitate resource mobilization, and reduce strategic uncertainty during growth phases [17, 30]. Moreover, access to skilled employees enhances innovation implementation capacity, enabling startups to convert ideas into scalable commercial outcomes.

Interestingly, educational level exhibited comparatively lower importance within the model, suggesting that formal education alone is insufficient to explain startup scalability. This finding aligns with literature indicating that experiential learning, entrepreneurial exposure, and social capital often outweigh academic credentials in predicting venture success [14]. Startup environments reward practical problem-solving, adaptability, and experimentation rather than purely theoretical knowledge. Recruitment practices based on affiliation and experiential fit rather than educational prestige have also been shown to influence organizational diversity and innovation outcomes [37]. Therefore, the study highlights a shift from credential-based evaluation toward competence-based entrepreneurial ecosystems.

Team diversity demonstrated moderate influence, reflecting both opportunities and challenges associated with heterogeneous startup teams. While diverse teams enhance creativity and knowledge recombination, excessive diversity may increase coordination costs and conflict risks, potentially constraining scalability if not properly managed. This dual effect corresponds with research documenting both positive and negative consequences of entrepreneurial diversity, particularly in failed startups where misalignment among team members contributed to organizational breakdown [11, 12]. The findings thus emphasize the importance of balanced diversity supported by strong leadership and shared strategic vision.

The results also underscore the interaction between human capital and external ecosystem factors. Venture capital financing, accelerator participation, and institutional support structures amplify the effects of human capital by providing access to networks, mentorship, and strategic resources. Studies on venture financing confirm that investors interpret founder competence and team capability as signals of startup quality and scalability potential [16, 26]. Furthermore, value-added activities of venture capital firms enhance organizational capabilities and support growth beyond financial investment alone [19]. The predictive importance of human capital observed in this study therefore reflects both internal competencies and ecosystem reinforcement mechanisms.

Machine learning modeling provided additional theoretical contributions by revealing nonlinear relationships between human capital variables and scalability outcomes. Traditional linear models often assume uniform effects, whereas the Random Forest approach demonstrated threshold and interaction effects among competencies. Recent research advocates using machine learning methods to evaluate early-stage investment decisions and entrepreneurial performance due to their ability to uncover hidden patterns within complex datasets [35]. The strong predictive accuracy obtained in this study supports the integration of data-driven analytics into entrepreneurship research and strategic decision-making.

From a broader perspective, the findings align with global evidence regarding startup development across different economic contexts. Studies examining startup acquisition, survival, and ecosystem growth consistently emphasize the role of human capabilities in navigating financial constraints, technological disruption, and competitive pressures [29, 34]. Digital transformation and geopolitical technological competition further intensify the need for adaptable entrepreneurial talent capable of sustaining innovation-driven growth [24]. Consequently, scalability should be conceptualized as a human-centered phenomenon embedded within evolving technological and institutional environments.

Gender perceptions and labor market expectations also indirectly influence scalability through their impact on talent attraction and organizational development. Research on gender stereotypes in technology startups shows that organizational image and leadership identity affect applicants' willingness to join startup teams, thereby shaping available human capital resources [32]. Similarly, commercialization studies highlight that entrepreneurial success depends on translating scientific knowledge into market applications through skilled human agents rather than technological invention alone [33]. These perspectives further reinforce the multidimensional nature of human capital effects identified in this research.

Finally, the findings contribute to entrepreneurship policy debates by demonstrating that scalable startup ecosystems depend primarily on talent development rather than financial subsidies alone. Policy initiatives promoting education, mentoring, and entrepreneurial capability development are likely to generate more sustainable economic outcomes than purely capital-oriented interventions [1]. Startup success therefore emerges from the cumulative interaction of innovation competence, technical mastery, managerial leadership, and organizational learning capacity, collectively forming a dynamic human capital system that drives scalable growth.

Although the study provides valuable insights into the relationship between human capital and startup scalability, several limitations should be acknowledged. First, the cross-sectional research design restricts the ability to infer causal relationships over time, as scalability is inherently a dynamic process that evolves throughout different stages of venture development. Second, the study relied on self-reported managerial data, which may introduce perceptual bias despite efforts to ensure accuracy through informed respondents. Third, the sample was limited to startups operating within Tehran, and therefore contextual institutional and cultural characteristics may limit generalizability to other entrepreneurial ecosystems.

Additionally, while Random Forest modeling captures complex relationships, machine learning methods may reduce interpretability compared with traditional theory-driven models, requiring cautious theoretical interpretation of predictive outcomes.

Future research could extend the present findings by adopting longitudinal designs that examine how human capital influences scalability across multiple stages of startup evolution. Comparative cross-country studies would help determine whether identified human capital drivers remain consistent across different institutional environments and economic systems. Further investigations may also integrate additional variables such as organizational culture, psychological traits of founders, digital capability maturity, and ecosystem-level interactions to develop more comprehensive predictive frameworks. Combining qualitative approaches with machine learning analytics could provide deeper understanding of underlying mechanisms through which human capital shapes entrepreneurial growth trajectories.

Startup founders and managers should prioritize investment in human capital development as a core strategic activity rather than treating it as a secondary administrative function. Building teams characterized by innovation competence, technical expertise, and strong managerial coordination can substantially enhance scalability potential. Entrepreneurial support organizations, accelerators, and policymakers should design programs that strengthen learning orientation, leadership capability, and skill development among startup teams. Investors may also benefit from incorporating structured human capital evaluation frameworks into funding decisions, recognizing that scalable growth is primarily enabled by capable people rather than technologies or financial resources alone. Finally, startups seeking sustainable expansion should cultivate adaptive learning cultures that continuously upgrade workforce competencies in response to changing technological and market conditions.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants. Written consent was obtained from all participants in the study.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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