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Classroom to Cultivation through Technology-Enabled Education for a Productive Agricultural System

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Classroom to Cultivation through Technology-Enabled Education for a Productive Agricultural System

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Abstract

This study is grounded within the investigation on understanding how Education 4.0 can lead to Productive Agricultural System (PAS) considering the mediating impact of Agricultural 4.0. and Institutional Effectiveness (IE). Further, the moderating roles of Cultural Resistance to Change (CRC), Research-Industry Interface (RII), and Public-Private Support Mechanism (PPSM) are assessed in the proposed framework. The proposed conceptual framework is tested by collecting data from 729 Agriculture students of 77 agricultural universities all over India using purposive and snowball sampling technique and performed mediation and moderated-mediation analysis using SmartPLS4.1 within the time frame of August 2025 to February 2026. The results indicate that IE ($\beta = 0.185$) plays a stronger mediating role compared to Agriculture 4.0 ($\beta = 0.041$), suggesting that institutional mechanisms are more critical in translating Education 4.0 into agricultural productivity. Further, CRC weakens the mediating path, whereas RII and PPSM strengthen the translation of Education 4.0 into PAS. The study provides empirical and theoretical insights for policymakers and academicians, and practioners to strengthen innovation-driven education–agriculture linkages for translating educational theoretical knowledge into applicable real-world agricultural application. The novelty of the study lies in integrating Education 4.0 and Agriculture 4.0 within a unified moderated mediation framework, highlighting the conditional role of institutional and ecosystem-level enablers in enhancing agricultural productivity.

Keywords: Education 4.0, Agriculture 4.0., Institutional Effectiveness, Cultural Resistance to Change, Research Industry Interface, Public-Private Support Mechanism, Productive agricultural system

1. Introduction

Indian agricultural sector is increasingly confronted with a triad of interconnected structural challenges, specifically detailed as food insecurity, declining farm profitability, and ecological unsustainability (Jatav & Naik, 2023). These three major challenges hinder in achieving a productive agricultural system (PAS) which is vital for an agro-reliant nation like India (Bhat et al., 2023) because more than 50% of the total headcount is dependent on agricultural system for livelihood, and the sector contributes 15% of the country's GVA to the economy (K.M et al., 2023). A PAS not only focuses on enhancing the profitability and ensuring food security but also emphasizes on sustainability of agricultural production (Gaffney et al., 2019) by conserving natural resources, maintaining ecological balance, and promoting

long-term resilience against climatic and economic uncertainties. Unfortunately, despite the progressive transition from Agriculture 1.0 (traditional subsistence farming) to Agriculture 2.0 (Green Revolution-led intensification), Agriculture 3.0 (precision and ICT-based farming), and Agriculture 4.0 (digitally integrated smart agriculture) (Barman et al., 2025), these long-standing challenges have remained predominantly unresolved, primarily due to the due to the superficial diffusion of agricultural technologies. This shallow diffusion in which technological innovations are introduced but not deeply internalized has resulted from inadequate skill development, limited digital literacy, and low adaptive capacity among stakeholders, which collectively constrain effective field-level adoption and application. This disconnects between technological advancements and their practical utilization highlights that the core constraint lies not only in the availability of innovations but in the capacity of stakeholders to absorb, adapt, and implement them effectively. Consequently, it can be understood that the failure to resolve the persistent agricultural challenges is not merely technological, but fundamentally educational, reflecting a systemic mismatch between knowledge systems and production systems (Arangurí et al., 2025). Despite the progressive transition offered by Agriculture 4.0, agricultural education has largely remained misaligned with the dynamic requirements of Agriculture 4.0, thereby hampering the effective translation of technical advancement into a productive agricultural system (PAS). Even if the education system has also evolved from Education 1.0 (learning and teacher-centric instruction), to Education 2.0 (structured knowledge dissemination), Education 3.0 (interactive and technology-enabled learning), and lately, Education 4.0, (digital technologies, experiential learning, and competency-based skill development), still, potential of Education 4.0 has remained underutilized in enabling the effective application of Agriculture 4.0 toward achieving a PAS.

India has one of the largest and most complex agricultural systems in the world, characterized by diverse climatic zones ranging from arid and semi-arid zones to humid tropical and coastal regions (Datta et al., 2022), varied soil types such as alluvial and black soils to red, lateritic, desert, and mountain soils (Bhattacharyya et al., 2013), wide-ranging cropping patterns encompassing seasonal cropping (Kharif–Rabi–Zaid cycles), step/terrace cultivation in hilly regions, and shifting (podu/jhum) cultivation, and extensive socio-economic conditions and frequent climatic stresses, ranging from droughts and heatwaves to floods (Datta et al., 2022), cyclones, and coastal salinity intrusion (Borthakur, 2022). This heterogeneous agro-system makes it challenging for achieving uniform growth while ensuring resource efficiency, equity, and environmental sustainability which necessitated the integrated implementation of Agriculture 4.0. (Ag4.0) and Education 4.0 (Ed4.0). In order to overcome the food crisis, Agriculture 4.0 has emerged as a transformative paradigm which has incorporated the adoption of smart technologies to enhance productivity, resource efficiency, and sustainability that are the essence of PAS. The use of smart technologies such as Internet of Things (IoT), artificial intelligence (AI) can be used for monitoring soil moisture and predicting rainfall, drought, floods, and cyclone risks (Klerkx et al., 2019), IoT-based sensors which can be helpful in developing image processing technologies for collecting crop images and environmental data (Liakos et al., 2018), and big data analytics for collecting real-time datasets generated from farm sensors, satellites, weather stations, and market platforms which can be useful in yielding prediction, crop pattern optimization, climate risk assessment, and forecasting market (Kamilaris et al., 2017). However, the effective adoption and utilization of these advanced technologies in agricultural sector necessitate a paradigm shift in the education system toward Education 4.0, which emphasizes digital literacy, interdisciplinary learning, critical thinking, and technology-driven skill development. Education 4.0 equips agricultural students with the competencies required to understand, adopt, and manage smart agricultural systems, thereby bridging the gap between technological innovation and practical implementation in the agricultural sector (O. Karani et al., 2024). It is obvious that agricultural students are not direct actors in agricultural systems, but their role will be paramount in facilitating dynamic transformation in the farming system. From equipping students with advanced analytical competencies, to experiential learning, digital skill, and deeper integration with industry and innovation ecosystems, extension activities, agri-tech entrepreneurship, industry absorption, and research–industry collaboration, they can act as carriers of technological knowledge

and enablers of Agriculture 4.0 applications. Therefore, the contribution of students to PAS is indirect but significant, as they bridge the gap between technological innovation and its field-level implementation through structured systemic channels. However, in absence of this crucial connection, students may only limit themselves to knowledge carriers rather than transformation agents, constraining the transition toward a productive agricultural system. Therefore, a targeted Education 4.0 intervention focused on developing technologically proficient, innovation-driven, and adaptive agricultural graduates becomes essential for fostering a PAS, as students serve as the primary carriers of knowledge transformation from theory to application.

2. Research Gap, Novelty, and Objectives

The escalating global demand for food, coupled with the pressing need for sustainable agricultural practices, necessitates innovative approaches and agricultural reforms to enhance productivity and resource efficiency (Şimşek, 2025). Despite ongoing reforms in India's agricultural education and digital farming sectors (Balkrishna et al., 2023), empirical research integrating Education 4.0 with Agriculture 4.0 remains limited. Most of the existing studies have focussed either on technological advancements (Agriculture 4.0) or pedagogical innovations (Education 4.0), without analyzing how education-driven digital competencies translate into agricultural productivity. In essence, empirical investigations examining the integration of Education 4.0 and Agriculture 4.0 are scarce or nearly absent. Second, limited attention has been given to the moderating roles of enabling mechanisms such as the Research–Industry Interface, Cultural resistance, and Public–Private Support Mechanisms that can strengthen or weaken these mediating relationships. Third, most of prior literature related to the current work has made use of linear cause–effect perspective, thereby overlooking the comprehensive investigation using multi-level, moderated–mediated pathways. Fourth, there is a dearth of literature examining the standpoints of agricultural students and professionals in adopting and disseminating Education 4.0 and Agriculture 4.0 innovations in India, which is focussed in the current research work for not just informing evidence-based and judicious policy interventions aimed but also strengthening the linkage between educational innovation and agricultural productivity.

To best of our knowledge, the current research work can be considered as the first empirical study to test the mediating roles of Institutional Effectiveness and Agriculture 4.0 in translating Education 4.0 outcomes into Agriculture 4.0. The study develops an integrated conceptual framework linking Education 4.0, Agriculture 4.0, Institutional Effectiveness, and Productive Agricultural Systems within the Indian context. Based on the gaps and novelty of the work, following research objectives are formulated:

RO1: To enquire the extent to which Education 4.0 can enhance productive agricultural system

RO2: To analyze the mediating role of Institutional Effectiveness and Agriculture 4.0 between education 4.0 and productive agricultural system

R03: To analyze the moderated mediating role of Research Industry Interface and Electronic Marketing system upon the mediating role of Agriculture 4.0 between Education 4.0 and productive agricultural system

RO4: To analyze the moderated mediating role of Public-Private Support Mechanism upon the mediating role of Institutional Effectiveness between education 4.0 and productive agricultural system

Section 3 outlines the theoretical framework followed by conceptual framework and literature review in section 4. Section 5 covers the methodology and analysis. Section 6 highlights the findings and discussion and Section 7 focuses on both theoretical and practical implications. Finally, Section 8 summarizes the key findings, with Section 9 acknowledging the limitations and possible future directions.

3. Theoretical Framework

Ed4.0 plays a central role in preparing agricultural stakeholders for Ag4.0 by equipping them with digital knowledge, skills and managerial capabilities. As outlined in Human Capital Theory (HCT) (Becker, 1918), these competencies are essential for adapting to advanced agricultural technologies for improving individual and system-level productivity. The current study believes that adopting Ed4.0 in the educational system will certainly strengthen the digital literacy, innovation capacity, and problem-solving skills of agricultural students who will be the stakeholders of agricultural system in the near future. Their education-driven capabilities, technically improved knowledge and skill will support better prediction, interpretation, and decision-making roles leading to higher profitability, stronger security, and more sustainable resource use in agricultural system. Further, this approach strengthens institutional capacity and aligns with the Institutional theory (DiMaggio & Powell, 1991) which highlights the value of institutional effectiveness in strengthening coordination, policy implementation, resource allocation, extension support, and technology diffusion in organizational settings. In the current context of the study, it can be understood as Ed4.0 alone may not directly transform agricultural system unless institutions effectively convert educational capabilities into productive, sustainable, and innovation-driven agricultural outcomes. However, this relationship becomes further stronger when it is supported by an effective public–private support mechanism (PPSM) and research industry interface (RII). The collaboration between Public and private enterprise and between universities and research institutions with private industry can be advantageous for the institutions as it can enable access to advanced technologies, industrial expertise, funding sources, digital infrastructure, training networks, and market linkages. The role of IE in amplifying the positive impact on PAS is explained by Dynamic Capabilities Theory (Teece et al., 1997) which explains how institutions sustain performance by continuously sensing emerging opportunities, seizing resources, and reconfiguring existing capabilities extended from PPSM. In addition to the existing factors, Cultural Resistance to Change plays a significant role in improvising the productivity of agricultural system by creating adaptive capability of the stakeholders. Deeply rooted socio-cultural values and norms often constrain the acceptance of technological and institutional innovations, thereby limiting the effective transformation of agricultural systems. However, utilizing Diffusion of Innovation Theory that emphasizes on diffusing Education 4.0 and Agriculture 4.0 practices in ways that are culturally compatible and sustainable can certainly enhance PAS (Rogers, 1983). In summary, the pathway to modern agriculture involves a blend of education, institutional support, and cultural adaptation working together to build a productive, secure, and sustainable agricultural future (Table 1).

Insert Table 1

4. Conceptual framework and literature review

4.1 Relationship of Education 4.0 and Productive Agricultural System

Ed4.0 refers to a forward-thinking framework that transformed traditional technique of learning in such a way that professional education can now hence be aligned with real-time production by integrating digital technologies, experiential learning, and industry relevance (Tikhonova & Raitskaya, 2023). When applied to agricultural sector, first, the agricultural students, agro-professionals, young scientists and researchers can use their digitally skilled and innovation-oriented knowledge in applying smart tools such artificial intelligence, Information of Technology, Machine Learning, automation, data analytics and remote sensing to enhance profitability from the farm output through efficient input use and precision farming (Maffezzoli et al., 2022). Second, Ed4.0 can be used in ensuring the food security by enabling learners to employ pedagogical innovations for predicting climate changes, analyzing the market forces of demand and supply, and estimate possible risk. Third, Ed4.0 not only carries the potential of ensuring food security and enhancing profitability, but also can drive agricultural sustainability by enabling learners to apply renewable energy systems, precision irrigation, and waste-to-wealth technologies in their practice for soil management and biodiversity preservation. These digital

technologies and innovative pedagogical approaches can enhance PAS by multiplying profitability, security and sustainability impact altogether. The comprehensive framework of PAS not only relies on productivity but also on how the system turns to be economically rewarding, environmentally sound, and socially stable, such that it can be efficiently carried forward for the future generation. Hence, it can be hypothesized that:

H1: Ed4.0 leads to PAS

4.2. Relation of Institutional Effectiveness with Education 4.0 and Productive Agricultural System

IE can be understood as the persistent excellence in planning, resource utilization, governance, execution, analyzing, and assessment of the programs and services extended by the Organization in alignment with its vision and mission (Bai Gokarna et al., 2022). In the context of agricultural education and development, IE can be mapped from how efficiently agricultural institutes and agro-based research and extended institutions utilize educational advancements in improving agricultural productivity. When Ed4.0 is adopted in the agricultural organizations, then students and researchers are skilled with digital pedagogy, experiential learning, and innovation-oriented curricula (Pogorelskaia & Várallyai, 2020) which proves to be effective in field for scientific experimentation such as precision farming, climate-smart agriculture, automated irrigation, and data-driven crop management (Khanna & Kaur, 2023) and also in building necessary governance structure, infrastructure, and policy support that can ensure PAS, characterized by higher profitability, production security, and environmental sustainability. Implementing Ed4.0 can lead to IE by developing research–industry collaboration and internship programs, identifying real-world challenges, developing creative technological solutions, and supporting capacity building through extension, training, and digital outreach initiatives (Esangbedo et al., 2023) which can ultimately result in PAS by multiplying profitability, security and sustainability impact altogether.

H2: Ed4.0 leads to IE

H3: IE leads to PAS

H6: IE mediates the relationship between Ed4.0 and PAS

4.3. Relation of Agriculture 4.0 with Education 4.0 and Productive Agricultural System

Ag4.0, also known as smart farming, and the fourth agricultural revolution aims at adopting next-generation communication, information and automation technology in managing production and distribution of agricultural products that can possibly enhance productivity and quality in one hand, and reduce cost of production and overutilization of non-essential fertilizers and pesticides on the other (Fragomeli et al., 2024). The application of Ag4.0. comprises of adopting precision farming, smart irrigation, automated crop monitoring, and predictive analytics for yield and resource optimization which can enhance output efficiency, resource optimization, waste reduction, automated crop monitoring and risk prediction (Maffezzoli et al., 2022). In implementing Ag4.0., Ed4.0. play a significant role as it equips the agricultural students, agro-professionals, young scientists and researchers with digital pedagogy, experiential learning, problem-solving skills, and innovation-oriented-analytical-thinking by integrating technology such as such artificial intelligence, Information of Technology, Machine Learning, automation, data analytics and remote sensing with practical application for practice (Fragomeli et al., 2024). The in-depth knowledge on technicalities and competencies can be translated to real-time agricultural operations through implementation of Ag4.0. which upon operationalization will not just improvise productivity by enhancing profitability, security, and sustainability but also supports environmentally responsible practices (Islam et al., 2024). Based on prior literature support, it can be assumed that Ag4.0 mediates the relationship between Ed4.0 and a PAS where theoretical digital skill and innovative attitude nurtured through next-generation education

can be transformed into applied, measurable agricultural outcomes, resulting in to a more resourceful, and sustainable agricultural sector.

H4: Ed4.0 leads to Ag4.0

H5: Ag4.0 leads to PAS

H7: Ag4.0 mediates the relationship between Ed4.0 and PAS

4.4. Relationship of Public-private support mechanism with Institutional Effectiveness, Education 4.0 and Productive Agricultural System

PPSM refers to a mutual cooperative arrangement between government entities (comprising of Ministries, departments, state-owned enterprises) and private stakeholders (business entities, local or international investors, financial agencies) that collectively aims at contributing to a common goal by sharing resources, expertise, and infrastructure (Agarwal et al., 2023). The collaboration encompasses integration of shared ideas, motive, technology, thereby linking public governance with private-sector innovation. The role of PPSM in bridging the gap between Ed4.0-driven learning outcomes and their IE is paramount. Considering public-owned agricultural universities, research institutes, and other extended department which can effortlessly provide subsidized farm products, policy direction and institutional legitimacy can collaborate with private enterprises such as start-ups and investment firms to bring profuse investment for infrastructural enrichment, technological innovation for output maximization, and market linkage and access for price stabilization. This synergy can enhance institutional capacity, accelerate the diffusion of advanced agricultural technologies with indigenous knowledge and practice thereby retaining long-term soil fertility, water efficiency, biodiversity, and ecological balance, and ensures that educational advancements translate into practical, scalable agricultural solutions (Sharma, 2015). This can eventually lead to PAS characterized by higher profitability, resilience, and sustainability. Hence, it can be hypothesized that:

H8: PPSM moderates the relationship of IE with Ed4.0 and PAS

4.5. Relationship of Research Industry Interface with Agriculture 4.0, Education 4.0 and Productive Agricultural System

Looking into the sphere of agricultural domain, RII can be understood as the dynamic collaboration between universities and research institutions with private industry that aims at translating educational theoretical knowledge into applicable real-world agricultural application through industrial funding (Soam et al., 2023). Implementation of Ed4.0. in academic and research institute will facilitate digitally proficient, research-oriented, and innovation-driven agricultural students, agro-professionals, young scientists and researchers with digital pedagogy, experiential learning, problem-solving skills, and innovation-oriented-analytical thinking to connect with industrial ecosystems for practical application and scalability of the research ideas. RII plays a significant role in bridging the gap between Ed4.0. and Ag4.0. by endorsing funded research projects, industrial seminar, webinar, workshop, and training program, and technology transfer partnerships, allowing educational knowledge to be refined and operationalized in field conditions (Haji Shahlehi et al., 2024). This can enhance the hallmarks of PAS by ensuring that benefits of next-generation education system can facilitate advancements in agricultural productivity and resilience. Hence**,** it can be hypothesized that:

H9: Research Industry Interface moderates the relationship of Ed4.0 with Ag4.0. and PAS

4.6. Relationship of Cultural Resistance to Change with Education 4.0, Agriculture 4.0, and Productive Agricultural System

Cultural Resistance to Change (CRC) can be understood as the reluctance of the individual or community or institution to adopt undesirable behaviour or attitude that can bring change in the status

quo (Danışman, 2010). In agricultural context, farmers, agricultural students, agro-professionals, young scientists and researchers, educators, may be reluctant or hesitate to adopt new technologies, practices, due to their pre-existing deep-rooted conventional beliefs, habitual behaviors, and social norms favouring traditional farming systems (Dessalegn et al., 2018). However, exhibiting cultural resistance marks their adherence to outmoded practices, scepticism toward new skills, and anxiety of mechanization or alteration in work patterns which in turn slows down their innovating capability. This resisting attitude propelled from societal roots and sociodynamic nature hinders practical implementation of Ed4.0 outcomes, which further condenses willingness of farmers, educators, and policymakers to invest and use Ag4.0 technologies (Islam et al., 2024). Consequently, this attitude hinders in ensuring food security, enhancing sustainability and achieving profitability which defines PAS. However, empirically diminutive is acknowledged about the extent to which CRC can hamper productivity and particularly in the integration of Ed4.0 and Ag4.0. Addressing this gap represents a novel step toward understanding behavioral and cultural dynamics that influence technological adoption in modern agricultural systems. Hence, the following hypothesis can be tested:

H10: CRC moderates the relationship of Ed4.0 with Ag4.0. and PAS

The proposed framework is depicted as follow:

Insert Figure 1

5. Data and Methodology

5.1. Data Collection

The study has analyzed the impact of Ed4.0 on the PAS, where the data is collected through online survey throughout India. The data for the current analysis was collected from the students of 77 agricultural institutions by using purposive sampling technique. The structure questionnaire was forwarded to the head of the institution for circulation among students in a time line of August 2025-February 2026. Before proceeding for the final round of data collection process, a pilot study was conducted in order to examine the practicality and feasibility of the methods to be used in a subsequently larger and more comprehensive investigation (Viechtbaueret al., 2015).

Insert Table 2

The pilot survey showed the study protocol's viability and a suitable data gathering timeline and sample size. Based on the findings of pilot study the final round of data collection was conducted via google form and gathered 729 final responses. Besides that, the study utilized Cochran's formula to determine appropriate sample size, as it is most suitable when the population size is undefined (Althubaiti, 2022). Applying Cochran's formula with a 95% confidence level and a 5% margin of error, the calculated ideal sample size for analysis was approximately 384 respondents. The demographic details are tabulated in Table 2.

5.2. Instrument and Scaling

The current study has reviewed prior literature to conceptualise the theoretical framework considered for the study. In order to assess Ag4.0, the study has adopted a 9-item scale developed by da Silveira et al. (2021), which was further modified and redesigned to measure the mediating role of Ag4.0 between ed 4.0 and PAS. Further, in order to measure the impact of Ed4.0 on modern agricultural practices of PAS, the current study adopted a 20-item scale developed by Sharma et al. (2024). In order to assess PAS, the study has considered three separate scale that are food security, agricultural profitability, 18-item scale developed by Alam et al. (2023) and agricultural sustainability a 38-item scale developed by Baxter & Chipulu (2023). Additionally, role of the CRC is mapped by using a 17-item scale developed by Zedda et al. (2023), which was further redesigned to measure the resistance of farmers to adopt modern technologies. In measuring IE between Ed 4.0 and PAS, the current study has adopted a 15-

item scale developed by Dhir (2024). In addition to this, PPSM is measured by using a 5-item scale developed by Okwelle and Wordu (2014) that emphasized on integration of public-private entities in adopting cutting-edge technology in agricultural universities. Ultimately, RII is traced by using a 16-item scale which was developed by Jamaludin et al. (2020) to measure the effect of academia-industry collaboration between Ed 4.0 and Ag4.0. The items of the constructs are further modified as per the requirement of the study. In this study, a five-point Likert scale was used, where "5" stands for strongly agree and "1" stands for strongly disagree.

5.3. Statistical Analysis

5.3.1. Measurement Model

The data is collected at the same time using a single self-reported questionnaire; hence the study may be susceptible to common method bias (CMB). As a statistical measure, the presence of CMB was tested by accessing the common method variance (CMV). Hence, first, in order to verify whether a single factor accounts for the majority of variance, Harman single factor test was performed (Ma et al., 2025). As the findings revealed that not a single factor account for the majority of variance (44% < 50%), hence, there was no major issue of CMB. Second, a full collinearity variance inflation factor (VIF) approach was employed which showed that all the variables in the current work projected a VIF value less than a threshold limit of 3.3, thereby confirming the absence of CMB (Malhotra & Ramalingam, 2025).

Further, the investigators have considered using SmartPLS version 4.1.1.8 software for conducting partial least square structural equation modelling (PLS-SEM) and to trace the mediation, moderation and moderated mediation relationship among the variables. The current research work preferred PLS-SEM over CB-SEM as the study aimed at predicting the results and not at testing or confirming the theory. Further, the conceptual framework designed for the current analysis is complex and comprises of multiple mediating and moderating relationships, thereby providing a flexible and reliable analytical framework for PLS-SEM compared to CB-SEM (Vuković, 2024). In addition to this, the current study has both reflective and formative constructs, hence the study used PLS-SEM over the CB- SEM However, before proceeding for the SEM analysis we assessed the internal consistency reliability of individual indicators through factor loading and at the construct level through Cronbach's alpha (α) and composite reliability (CR). Only items with significant factor loadings and more than 0.50 were retained (Dash et al., 2025). After every deletion, the effect of deletion on reliability and convergent validity was examined through Cronbach's alpha, Rho_a, and AVE to ensure that such a deletion did not compromise the quality of the measurement. As depicted in Table 3, the values of Cronbach's alpha and CR for both the lower and higher-order constructs were above the acceptable threshold (recommended value>0.6), representing good internal consistency) reliability (Hair et al., 2010).

Insert Table 3

The convergent validity was examined using the average variance extracted (AVEs) values for all latent constructs, and the results showed that all AVE values were more significant than 0.5, as Fornell and Larcker (1981) recommended. Further, the Heterotrait-Monotrait (HTMT) ratio is calculated to test the divergent validity among the constructs. The result ranged between 0.466 and 0.822, showing a satisfactory discriminant validity among the constructs (Hsu et al., 2016).

5.3.2. Structural Model

The current study has tested the structural model using coefficient of determination (R^2), predictive Relevance (Q^2) and effect size (f^2) to justify that the model is not just statistically significant, but also meaningful and predictive (Hair et al., 2017). First, in order to test how much of the variation in endogenous variable is explained by exogenous variables, R^2 is estimated. The results indicate that the model explains 48.8% of the variance in IE, 69.9% in Agri 4.0, and 75.7% in PAS, thereby demonstrating a weak to moderate explanatory power across the endogenous constructs. Second, to

understand importance of each variable, f^2 was estimated which revealed that it ranges from 0.008 and 0.491 that is higher than the threshold value of zero. Third, to verify the predictive relevance, Q^2 was tested which revealed that Q^2 value of IE (0.479), Agri 4.0 (0.694), and PAS (0.642) noted to be greater than the threshold value of zero. The proposed conceptual model is tested by using a nonparametric bootstrapping method with 5,000 samples. Table 3 tabulates the direct association among the constructs. Further, the hypothesized relationships among latent constructs are tested using path coefficient (B), t-statistics and 95% confidence interval (CI) values.

6. Results and Discussion

6.1. Direct Path Analysis

After confirming the model validity and reliability, path analysis was employed to investigate the structural relationships, including direct, mediation, and moderated-mediation effects among the proposed variable. It is observed from the direct path analysis all the variables are significantly related. As depicted in Table 4, Ed4.0 is significantly influencing IE, Ag4.0, and Productive Agriculture System. This describes that with the introduction of Ed4.0, education integrates with the digitalisation that enables smart learning practices, data driven decision making and skilled based learning that enhances the competency of the agricultural students and professionals for the era of smart and sustainable farming (O. Karani et al., 2024). As a result, institutions become more adaptive, transparent, and outcome-oriented, ultimately strengthening their capacity to deliver sustainable agricultural education and innovation (Arangurí et al., 2025). In addition, this transformation in Indian agricultural universities enables them to implement Ag4.0 that integrates IoT, AI and ML in the agricultural practices. Ultimately, the amalgamation of digitalisation and modernisation in both educational sector and agricultural sector leads to PAS by integrating agricultural profitability, food security and sustainability (Pogorelskaia & Várallyai, 2020).

Insert Table 4

Further, while analysing the direct relationship between IE and PAS, it is found that IE plays a pivotal role in enhancing the productivity and sustainability of the agricultural system (Singh, 2000). Effective educational institutions ensure efficient governance, quality education, and research-driven innovations (Gelgo et al., 2023) that strengthen human capital and facilitate technology transfer in agriculture. When these institutions function with strategic vision, accountability, and stakeholder engagement, they create an enabling environment for innovation adoption, improved farm management, and resource optimization (Kohl, 2023). Similarly, while analysing the relationship between Ag4.0 and PAS, the result revealed a significant positive association between the variables. This indicates that adoption of modern technologies such as precision farming, data-driven irrigation, smart sensors, and automated systems, these will not only enhance the profitability and food security, but also make the agricultural productive system sustainable (Mgendi, 2024).

6.2. Mediation Analysis

In the second phase while analysing the mediating role of the proposed variables, it is observed that both the mediators i.e. IE and Ag4.0 are partially mediating the association between Ed4.0 and PAS, this indicates that the direct path between the independent variables (Ed4.0) and the dependent variable (PAS) remains significant even after including the mediators (IE and Ag4.0) in the model (Figure 2).

Insert Figure 2

Further, it can be seen from the findings that IE is significantly mediating the relationship between Ed4.0 and PAS. This indicates that with the integration of IE, the educational innovation transfer to the organizational practices which improves the teaching-learning practices, research and technology adoption (Bai Gokarna et al., 2022) that ultimately improves the PAS (Fuglie et al., 2017). In addition to this, Ag4.0 significantly mediates the association between Ed4.0 and PAS, which can be understood

as, Ed4.0 equips the students of agriculture domain with the usage of ML, IoT, and AI in the farming process (Bampasidou et al., 2024) whereas Ag4.0 translate these skills into practice (Fragomeli et al., 2024) and ultimately leads to PAS.

6.3. Moderated Mediation Analysis

In the final phase, a moderated mediation analysis was conducted, revealing that the PPSM, when combined with Ed4.0, it positively influences IE, which subsequently enhances the PAS. In this context, it can be argued that the synergy between public and private actors facilitates the provision of advanced technology, investment, policy support, infrastructure, and innovation capacity (Hermans et al., 2019). This combined support reduces barriers to adopt advanced technology among farmers, while simultaneously strengthening the translation of Education 4.0 capabilities into practical agricultural outcomes ultimately resulting in PAS (Klerkx et al., 2019). In addition to this, the analysis of the moderating role of CRC indicates a negative interaction between CRC and Ed4.0 on Ag4.0 (Fragomeli et al., 2024), ultimately constraining productive agriculture. This effect arises from limited acceptance of emerging technologies, persistent traditional mindsets, inadequate digital literacy, and apprehension toward digital transformation (John et al., 2023), all of which prevent modernization and innovation within the agricultural sector. Conversely, the interaction between the RII and Ed4.0 demonstrate a positive influence on Ag4.0, thereby enhancing the PAS (Dang et al., 2024). The synergy between RII and Ed4.0 fosters research-driven innovation, bridges the knowledge–application gap, and facilitates the diffusion of smart and sustainable agricultural practices, collectively contributing to improved productivity and sectoral advancement (Wang & Yu, 2023).

7. Conclusion

The current study has empirically examined the impact of Ed4.0 on PAS with the mediating variables IE and Ag4.0. In addition, the moderating roles of PPSM, RII, and CRC were assessed. The findings reveal that IE partially mediates the relationship between Ed4.0 and PAS, suggesting that the mere inclusion of technologies such as AI, ML, and IoT in educational curricula is insufficient unless they are effectively operationalized to generate measurable agricultural outcomes. Furthermore, Ag4.0 also partially mediates this association, indicating that translating theoretical knowledge into practical field applications significantly enhances the productivity, sustainability, and overall effectiveness of the agricultural system. However, the findings also reveal that contextual moderators significantly shape these dynamics. PPSM and CRC weaken the effectiveness of Ed4.0 by introducing governance constraints and socio-cultural inertia, whereas a strong RII reinforces innovation diffusion and technology transfer. Overall, the results confirm that the integration of digital education and smart agriculture can collectively ensure profitability, food security, and sustainability. Strengthening institutional capacity, mitigating cultural and structural barriers, and deepening academia–industry collaboration are essential steps for advancing a digitally empowered and sustainable agricultural ecosystem in India.

8. Implications for Practice

This study offers noteworthy theoretical outline and practical insights for policymakers, academicians, and researchers. Initially, from a theoretical perspective, the study enriches the literature by elucidating how Ed4.0 facilitates to PAS through IE and Agri4.0. Consequently, based on the results, first, policymakers can be advised to set regulations that fosters introducing more AI competent institutions or organizations, appointing skilled faculties and innovation-driven curriculum for strengthening Ed4.0. Second, in order to enhance IE, government should emphasize on systematic evaluation of monitoring and assessment mechanisms to ensure that next-generation educational outcomes are successfully implemented at the ground level. This will increase the profitability, security, and sustainability of the agricultural sector. Moreover, the results also revealed that Ag4.0 mediates the relationship between Ed4.0 and PAS. Third, aligning with the findings of the research work, more priority needs to be given

to data-driven climate mapping and problem-solving technologies that can be helpful in achieving agricultural security. Fourth, as analyzed in the study, PPSM negatively moderates the mediating impact of IE on Ed4.0 and PAS. Hence, it can be suggested that the institution should collaborate with a single entity at a time, either with the public or private sector, in order to avoid overlapping mandates, conflicting interests, and diluted responsibility. Fifth, policymakers and researchers should collaborate to set up agricultural technology innovation labs in educational institutions and conduct workshops that can enhance awareness and adaptability toward Ag4.0. Sixth, this is evident from the result that cultural resistance stemming from traditional mindsets, limited exposure to digital tools, and a deep-rooted reliance on conventional farming hinders farmers from adopting Ag4.0. To overcome the conventional attitude, the policymaker should promote behavioral changes among the farmers by conducting awareness campaigns, demonstration-based training, and the inclusion of digital literacy programs that can possibly pave the way for a more inclusive and technology-driven agricultural ecosystem.

9. Limitations and Future Scope

Despite offering notable results, the current analysis can be criticized from methodological and contextual grounds. From methodological perspective, it can be observed that the study has adopted a cross-sectional research design by collecting data in between a stipulated time frame from June–September 2025. As a result, one of the limitations of the study can be thought of restriction in establishing a long-term causal inference of Ag4.0 and IE on relationship between IE, and PAS. In this case, future research endeavor may consider adopting longitudinal or time-series approaches to capture the dynamic findings. The findings of the study are mapped from sample 410 stakeholders under 77 agricultural universities, thereby not fully representing the extended but significant stakeholders like farmers, agri-tech entrepreneurs, policymakers, and extension workers. Future research can possibly focus on multi-stakeholder sampling design for holistic findings. From contextual perspective, it can be suggested that as the current study has not captured the potential contextual variables such as Industry 4.0., Leadership orientation, Environmental Governance, hence, future research work could incorporate the same for enriching the theoretical depth of the model.

10. Declaration by Authors:

Conflict of interest: The authors declare that they have no conflict of interest. The authors have no relevant financial or non-financial interests to disclose.

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Ethical Statement: This study was approved by the Ethics Committee of Kalinga Institute of Industrial Technology under approval number KIIT/ULEC/031/2025, in accordance with the ethical guidelines and regulations for research involving human participants.

Data availability: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Consent to Participate: Informed consent was obtained from all participants in the study. All human-related procedures were performed in accordance with the relevant institutional guidelines and ethical standards.

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Contribution of authors: SD has collected the data. SD and SP have collectively contributed to analysis tools. ND, SK, and JS have designed the framework and SD, SM and SC performed the analysis. All the authors have substantially contributed towards writing and editing the manuscript.

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List of Tables

Table 1 Theoretical Framework

Sl.No.	Theory	Adopted from	Relevance	Hypothesis
1	Human Capital Theory	Becker, 1918	Explains how investment in education, skills, and training, enhances an individual's or an organization's productivity, which in turn contributes to economic growth and development.	H1, H5, H6, H7
2	Institutional Theory	DiMaggio & Powell, 1991	Determines how formal institutions, governance structures, rules, policies, and organizational practices can shape knowledge and innovation adopted and translated into system-level outcomes.	H2, H3, H4
3	Dynamic Capabilities Theory	(Teece et al., 1997)	Elucidates how institutions sustain performance by continuously sensing emerging opportunities, seizing resources, and reconfiguring existing capabilities extended from PPSM.	H8 and H9
4	Diffusion of Innovation Theory	Rogers, 1983	Clarifies how the adoption of new technologies depends on their compatibility with existing socio-cultural values and norms.	H10

Source: Authors' Own

Table 2 Demographic Details

Variable	Category	Frequency	Percentage
Gender	Male	532	73
	Female	197	27
Age Group (years)	< 20	204	28
	20 - 25	262	36
	26 - 30	168	23
	>30	102	14
Degree Programme	B.Sc. (Agri/Hort)	139	19
	B. Tech (Agri Engg)	321	44
	M.Sc. (Agri)	139	19
	PhD	131	18
Participation in Research or Industry Projects	Yes	525	72
	No	204	28
Access to Smart Learning Resources / ICT	Yes	620	85
	No	109	15
Region of University	North	153	21
	South	168	23
	East	153	21
	West	146	20
	Northeast	117	16

Source: Authors' Own

Table 3 Model Validity Measures

Construct	Items	Factor Loadings	AVE	CR rho_c	CR rho_a	Cronbach
Education 4.0 (Ed 4.0)	My classes use modern teaching methods like interactive games, simulations, and virtual or augmented reality to make learning engaging. (Ed1)	0.862	0.670	0.890	0.842	0.835
	We regularly use digital tools like Kahoot, Quizlet, or similar apps for quizzes, tests, and other assessments. (Ed2)	0.797				
	I am encouraged to develop important skills such as problem-solving, critical thinking, teamwork, and communication. (Ed3)	0.864				
	I am taught how to use technology responsibly, including understanding online ethics and safety. (Ed4)	0.745				
Institutional Effectiveness (IE)	My institution has a dedicated ICT office that effectively manages the university/college's digital and technological needs. (IE1)	0.743	0.644	0.878	0.816	0.814
	Classrooms are equipped with flexible layouts and modern technology that allow students and teachers to connect	0.771				

	wirelessly and collaborate easily. (IE2)					
	The digital infrastructure provides open access to scientific data and knowledge that supports research, innovation, and commercialization opportunities. (IE3)	0.864				
	I have access to online learning platforms and digital resources such as blogs, vlogs, wikis, Google Classroom, Edmodo, and academic databases like Google Scholar or EBSCO host. (IE4)	0.826				
Agriculture 4.0 (Ag 4.0)	I have access to sufficient digital resources (e.g., internet, agri-tech software, devices) to integrate Agriculture 4.0 practices through Education 4.0 platforms (Agri1)	0.628	0.653	0.881	0.835	0.816
	I find Education 4.0 tools easy to use for teaching and conducting research related to Agriculture 4.0 (e.g., precision agriculture, IoT, drone technology). (Agri2)	0.841				
	I intend to continue using Education 4.0 technologies to support teaching and research on Agriculture 4.0 in the future (Agri3)	0.870				
	I may consider using Education 4.0 tools occasionally to complement instruction or research related to Agriculture 4.0 (Agri4)	0.867				
Public-Private Support Mechanism (PPSM)	I am aware of government initiatives (e.g., NEP 2020, Digital India) supporting the integration of Education 4.0. (PPSM1)	0.749	0.688	0.898	0.848	0.847
	I know of private organisations or ed-tech companies collaborating with educational institutions to promote digital education. (PPSM2)	0.861				
	My institution has received support from public or private entities for Education 4.0 (PPSM3)	0.852				
	Public-private partnerships have improved the quality of digital teaching and learning in my institution. (PPSM4)	0.851				
Research Industry Interface (RII)	In most research projects, the objectives and potential solutions are jointly determined by university and industry partners (RII1)	0.842	0.547	0.825	0.790	0.733
	There are regular events (e.g., seminars, workshops) where research outcomes are shared with industry collaborators (RII2)	0.834				
	Industry partners frequently recruit PhD researchers from university programs involved in collaborative projects (RII3)	0.591				
	University-industry collaborations have generated substantial investments in new R&D projects or programs (RII4)	0.659				
Cultural	Farmers are often unable to adopt modern	0.818	0.719	0.911	0.872	0.870

Resistance to Change (CRC)	technologies due to limited access to credit and financial resources. (CRC1)					
	Traditional beliefs and customs discourage farmers from changing their established farming methods. (CRC2)	0.843				
	Lack of adequate technical knowledge limits farmers' understanding of modern agricultural tools and methods. (CRC3)	0.881				
	Farmers tend to avoid change because they perceive it as risky or uncertain. (CRC4)	0.848				
Productive Agriculture System (PAS)	My education includes AI, drones, IoT, and precision farming tech that can improve yields and farm profits. (AP1)	0.729	0.524	0.930	0.918	0.917
	I learn to use digital tools (farm management software, GIS, analytics apps) that help reduce costs and improve economic outcomes. (AP2)	0.706				
	The curriculum links modern tech methods directly to increasing farm productivity and profitability. (AP3)	0.670				
	Education 4.0 equips me with skills (e.g., data-driven decision making, cost analysis, entrepreneurship) that support running or advising profitable agricultural operations (AP4)	0.699				
	The use of advanced technologies in my education (like drones, AI, and data tools) helps me understand and address food security challenges. (FS1)	0.750				
	Digital tools and platforms provided through Education 4.0 help me explore solutions for improving food availability, access, and sustainability. (FS2)	0.751				
	My learning experiences connect agricultural knowledge with real-world food security issues such as hunger, nutrition, and resource management. (FS3)	0.741				
	Technology-enabled practical training (like innovative farming projects or simulations) prepares me to contribute to food security at local and global levels. (FS4)	0.750				
	My exposure to Education 4.0 has motivated me to apply eco-friendly methods (e.g., organic farming, precision agriculture) in real-world agricultural practices. (AS1)	0.752				
	I have learned to evaluate the full life cycle of agricultural inputs (e.g., seeds, fertilisers, machinery) to minimise environmental harm. (AS2)	0.664				
	Technologies introduced in Education 4.0	0.754				

	(e.g., sensors, data analytics, AI) have improved my ability to plan sustainable farming systems. (AS3)					
	Through digital learning tools and platforms, I have gained knowledge on reducing the carbon footprint in agricultural production. (AS4)	0.659				

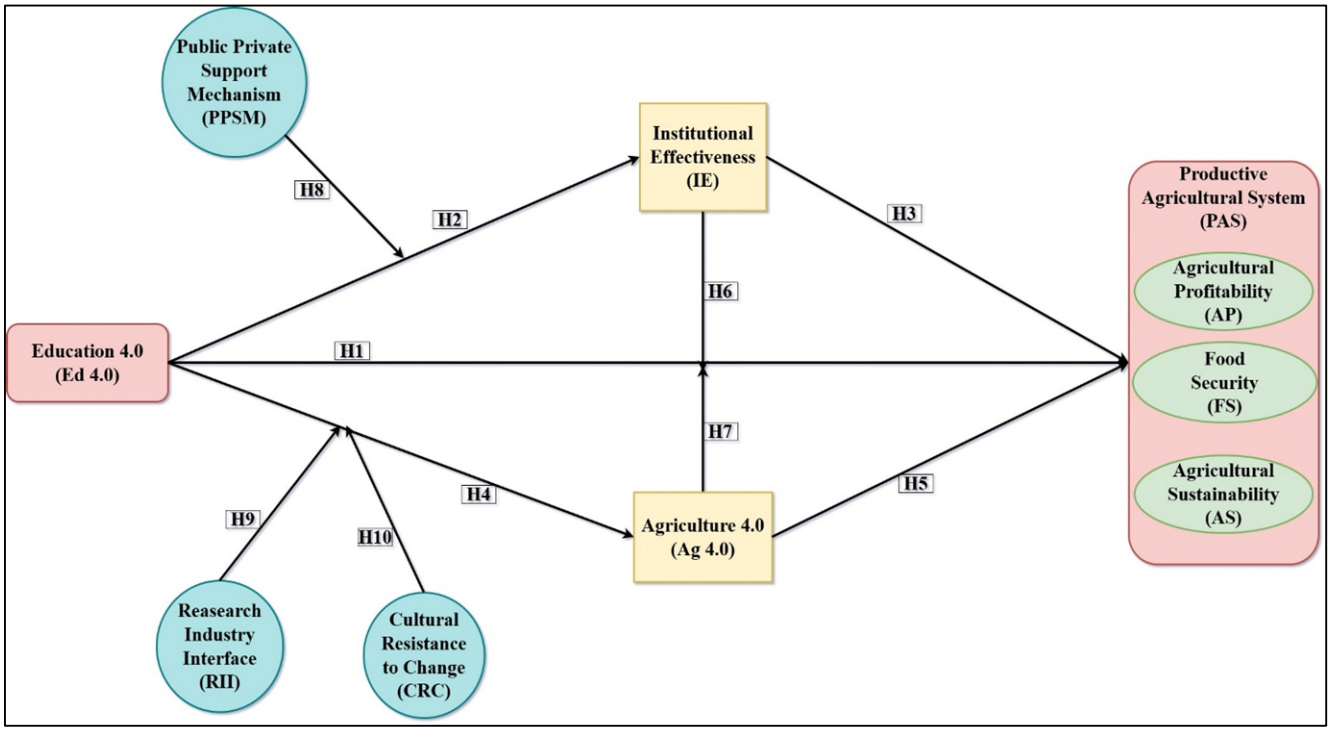
Source: Authors' Own

Table 4 Structural Equation Modelling Results

Path Analysis	Coefficient (β)	T statistics	P values	LL	UL
Direct Path Analysis					
Ed 4.0 -> Ag 4.0	0.173	5.896	0.000	0.116	0.231
Ed 4.0 -> IE	0.380	8.878	0.000	0.292	0.462
Ed 4.0 -> PAS	0.265	8.419	0.000	0.204	0.325
IE -> PAS	0.496	15.790	0.000	0.437	0.560
Ag 4.0 -> PAS	0.227	7.556	0.000	0.168	0.286
Mediation Analysis					
Ed 4.0 -> IE -> PAS	0.188	7.978	0.000	0.143	0.236
Ed 4.0 -> Ag 4.0 -> PAS	0.039	4.484	0.000	0.024	0.058
Moderated Mediation Analysis					
PPSM x Ed 4.0 -> IE -> PAS	0.032	1.908	0.056	0.000	0.065
CRC x Ed 4.0 -> Ag 4.0 -> PAS	-0.032	3.263	0.001	-0.053	-0.014
RII x Ed 4.0 -> Ag 4.0 -> PAS	0.028	3.069	0.002	0.011	0.048

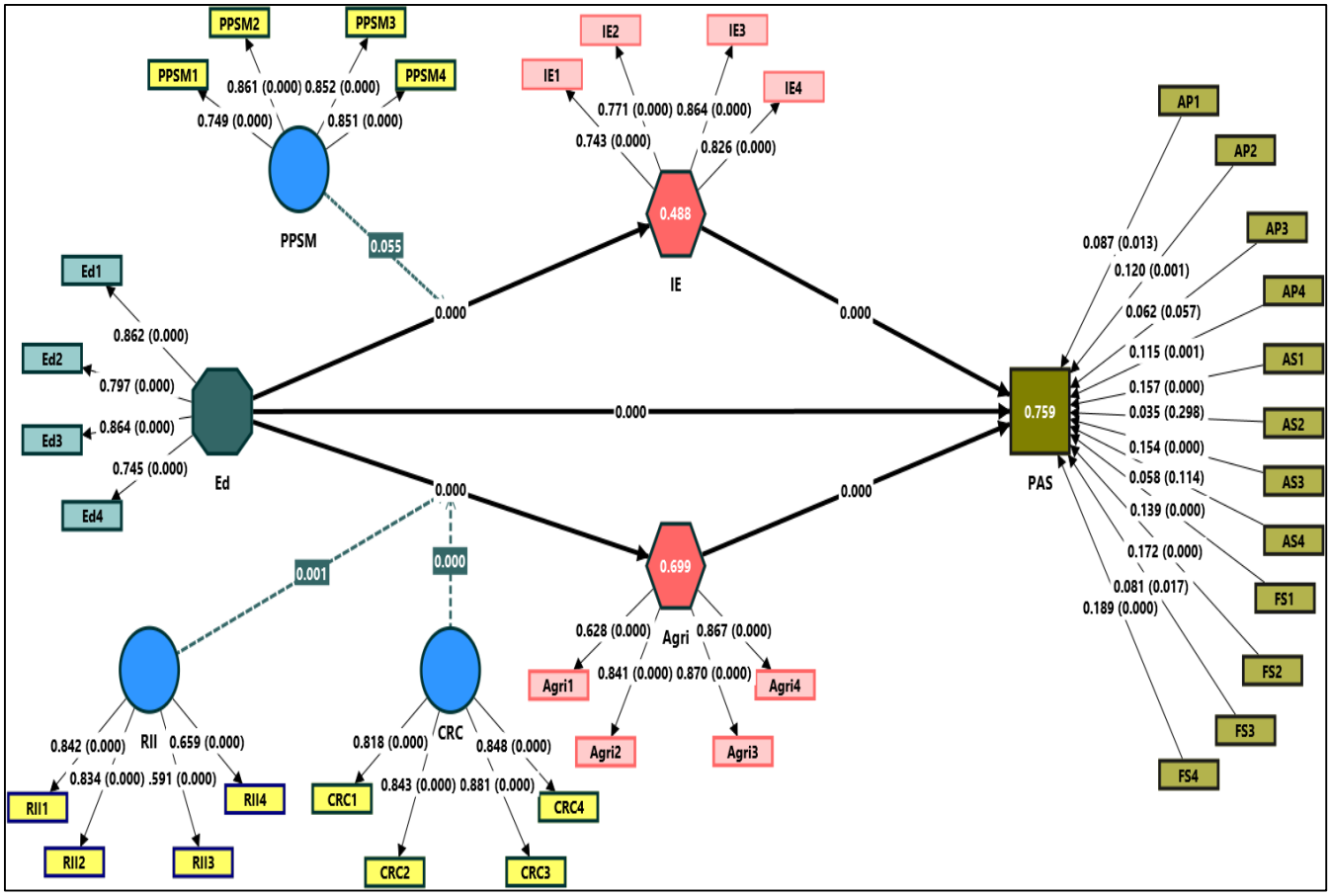
Note: LL- Lower Limit, UL- Upper Limit
Source: Authors' Own

List of Figures



Source: Authors' Own

Figure 1 Conceptual Framework



Source: Authors' Own

Figure 2 Structural Equation Modelling