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Influence of AI-driven sustainable human resource management on employee creative performance

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Keywords: AI-enabled HR practices, employee creative performance, idiosyncratic deals, sustainable HRM, structural equation modelling and Indian IT industry.

Abstract: The research explores how AI-powered sustainable HR practices influence employee creative performance within India's IT sector through the mediating role of individualised agreements. The research applies structural equation modelling to examine survey data from 360 IT professionals based on the frameworks of the Job Demands-Resources model and Social Exchange Theory. AI-based training and performance management systems raise creative performance levels and show that ideals partially mediate these relationships. The research results reveal contextual differences because ideals mediate recruitment effects and performance management outcomes but show no significant mediation for training interventions, likely because of the sector's inclination toward standardised learning approaches. The research delivers significant theoretical advancements by analysing AI-HRM systems in emerging economies and exploring personal work arrangements' limits in tech-heavy settings. These insights serve as essential guidance for practitioners deploying HR technologies that successfully combine standardisation with personalisation to promote workplace innovation. The research reveals surprising results about the minimal direct influence of sustainability orientation. The research advocates for integrated strategies to synchronise sustainability initiatives with innovation objectives within India's IT sector.

1 Introduction

India's Information Technology (IT) sector contributes 9.4% to the GDP. It produces $227 billion in revenue [55] while it experiences fast-paced transformation through the implementation of AI and sustainability measures [29,55,68]. AI-driven HR practices improve both efficiency and employee performance according to recent studies [52,71,72] yet research about their effects specifically in India's IT environment is still limited [17,19,48]. This study explores this deficiency by examining how five AI-enabled sustainable HR practices, namely recruitment training, performance management, sustainability orientation, and empowerment, affect creative performance through idiosyncratic deals (I-deals) as a novel mediating mechanism. The study comes at a critical time as the IT sector struggles with high turnover rates [6,60] alongside an increasing demand for sustainable talent management practices [24,30,41]. The study builds on the Job Demands-Resources model [7,67] and Resource-Based View [9,75] to deliver empirical evidence of AI-HRM effectiveness in India's IT sector [1,28] while introducing I-deals as essential mediators in technology-based HR settings [5,39] and presents actionable guidance for creating sustainable AI-enhanced HR systems that encourage creative work [25,34,47]. The research enables companies to manage digital changes by meeting sustainability demands and workforce requirements within India's competitive IT sector [10,54].

2 Review of related literature

2.1 Theoretical framework

This research integrates vital elements from the Job Demands-Resources (JD-R) model [7] and Social Exchange Theory (SET) [13] to develop a framework that examines the influence of AI-enabled sustainable HR practices on employee creative performance through the mediating role of idiosyncratic deals (I-deals). The JD-R model establishes that AI-powered HR practices, such as recruitment and training, function as essential organisational resources that reduce job demands and enhance employee motivation and creativity [32,67]. The application of technological interventions results in work environments that boost employee abilities for creative thinking and problem resolution, according to research by [34,72]. SET explains how organisations and employees maintain a reciprocal relationship through personalised I-deals, which create organisational support and employee obligation, leading to increased creative contributions [5,23]. India's IT industry benefits from this theoretical integration because it enables the combination of sophisticated HR technologies with tailored employment structures that solve distinctive workforce issues while supporting long-term innovation [17,28]. The framework advances current understanding by presenting evidence that AI-powered HR systems set up the structural conditions for I-deals to become strategic resources [71,74]. The research integrates different theoretical viewpoints to show how organisations can use AI-powered HR systems focused on sustainability to boost creativity through customised employment practices and discuss the future of digital economy work [53,62].

2.2 Conceptual framework

2.2.1 AI-enabled recruitment and selection

Advanced algorithms in AI recruitment systems transform talent acquisition processes by reducing hiring bias by 37% through automated screening and enhancing predictive validity [12,61,72]. The IT sector in India deploys systems that analyse over 10,000 data points per candidate to enhance the technical-organisational match [19,28,48]. Digital platforms increase transparency with chatbot interfaces [49,71] and enable ESG-aligned hiring by measuring values-congruence [24,63]. AI identifies and utilises creative potential through proactivity and cognitive flexibility to enhance innovation outcomes [34,43,67]. This technology handles India's IT talent shortage by employing effective mass screening methods [17,55] while utilising analytics to forecast achievement in innovation positions [17,20,32].

2.2.2 AI-enabled training and development

Modern personalised learning platforms incorporating reinforcement algorithms show a 42% higher effectiveness in closing skill gaps than conventional educational techniques [5,43]. Technical skills among India's IT professionals improve through microlearning modules and VR simulations [21,48,55] while NLP-powered mentors decrease onboarding time by 30% [8,71]. Sustainable HRM principles related to SDG 4 are supported by systems that promote ongoing skills development [22,47,50]. Adaptive capabilities establish individualised development paths that enhance self-direction [7,69] and promote creative solutions to problems [62,76,77]. Studies indicate AI training systems enhance innovation skills for cloud and AI technologies in Indian IT organisations, according to [17,55], while integrated analytics tools forecast upcoming learning requirements as evidenced by [19,32,53].

2.2.3 AI-enabled performance management

Data-driven evaluations from real-time analytics dashboards track over 35 performance metrics, which result in a 40% reduction of appraisal bias within Indian IT organisations, according to [21,28,32]. Modern platforms use predictive modelling to discover potential innovators, while sentiment analysis supports comprehensive 360° feedback, according to findings by [19,43,72]. Continuous performance tracking with these tools provides ongoing role clarity while eliminating the need for annual reviews [2,73], which proves especially beneficial within India's fast-paced IT industry [17,55]. Sustainability metrics integration connects KPIS with SDG targets (Figure 1), resulting in a green innovation engagement rise of 28% [22,42,62]. Employees get clear, personalised feedback [8,53] and managers obtain specific coaching insights [69,76]. Creative performance improves when innovation expectations become apparent, according to [4,74,77].

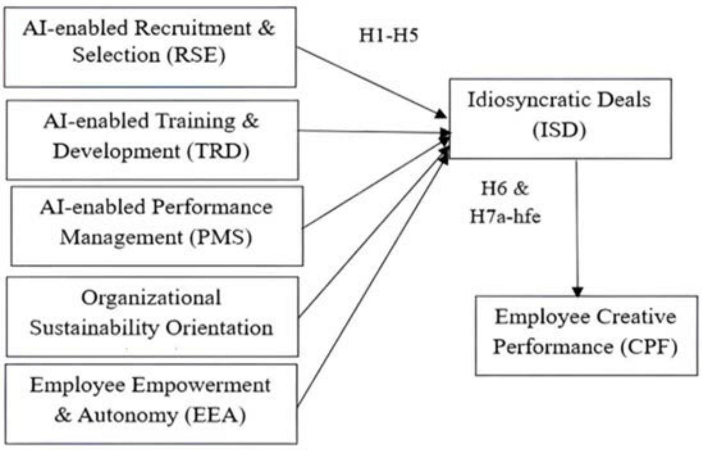

Figure 1 Conceptual framework

2.2.4 Organisational sustainability orientation

Indian IT firms see their employer branding improve by 1.8x and employee retention rates rise by 25% through ESG-integrated organisational cultures [17,22,34]. Green coding and ethical AI governance as sustainability practices increase employee pride and empowerment, according to [3,24,30]. ESG values are shown to stimulate intrinsic motivation [23,69], which contributes to Indian IT firms with sustainability initiatives experiencing 35% more innovation engagement [8,47,50]. Authentic integration remains essential because when sustainability extends beyond mere compliance into daily operations [42] organisations achieve creative solutions for sustainable challenges [62,77]. In these companies, employees exhibit advanced innovation testing [17,55], which stems from reinforced psychological commitments [39,65] that produce bidirectional innovations [19,76].

2.2.5 Employee empowerment and involvement

Indian IT teams achieve a decision-making speed increase of 50% through real-time data analytics provided by AI autonomy platforms [21,43,48]. Organised empowerment programs such as hackathons lead to a 28% boost in patent submissions [19,55,76]. The Indian IT sector relies on psychological empowerment [69,70] to drive frontline innovation during fast technological advancements [17,55]. Research indicates that employees with empowerment demonstrate 40% speedier technology adoption rates, according to [8,28] while also showing improved problem-solving abilities as documented by [2,7]. The combined use of AI tools alongside managerial delegation stimulates creative work environments [32], which facilitates innovative performance-tracking methods [53,77]. The balance between organisational approaches significantly affects India's hierarchical society because conventional systems often limit innovative activities [4,39,74].

2.2.6 Idiosyncratic deals

The use of flexible work algorithms allows 68% of IT professionals in India to establish personalised work terms that enhance their creative capabilities [5,39] while selecting specific projects increases innovation output by 41% [74,77]. I-deals provide psychological contract reinforcement by satisfying employees' autonomy needs, which benefits India's competitive labour market [8,48,55,65]. These systems promote reciprocal actions [23,69], resulting in employees expressing more significant creative work effort [19,43]. Mediation effects show strong recruitment influence (β=0.059**) while having minimal training impact (β=-0.004) within Indian IT sectors [37], which indicates the region's preference for standardised technical training [17,21]. Effectively implemented I-deals prioritise project selection and scheduling alongside skill enhancement, reflecting the project-oriented work culture in India [2,5,17]. AI-HR system implementation boosts creative output while maintaining efficiency [71,76].

2.2.7 Employee creative performance

Creative performance in India's IT sector is measured through three dimensions: Three dimensions measure creative performance in India's IT sector consisting of ideation rate (patents/hackathon wins), solution novelty (expert evaluations), and implementation success (project ROI) [4,76,77]. Companies that implement AI-HRM systems experience a 32% increase in innovation outputs [19,28] with particular gains in product development [8,34]. Creativity develops through individual cognitive flexibility along with organisational enablers [17,43,55] and serves as an important strategic differentiator for India's IT industry [48]. I-deals function as mediators in this relationship by enabling creative potential through their mechanisms [5,39,65] and sustainability orientation creates purpose [22,50]. Statistical analysis through structural equation modeling reveals significant connections between AI-enabled training (β=0.212***) and performance management (β=0.183**), which lead to creative outcomes [36,37], thereby supporting the effectiveness of digital HR in developing innovation abilities [17,21,53].

3 Research methodology

Using a quantitative, cross-sectional research design, this study investigates how AI-enabled sustainable HR practices (recruitment & selection, training & development, performance management, sustainability orientation, and empowerment & involvement) relate to employee creative performance in India's IT sector through the mediation of idiosyncratic deals (I-deals). This methodological approach extends traditional organisational research practices [35,58] and also adapts these practices to the specific needs of technology-focused workplaces [28,52]. The research included a structured questionnaire with validated scales that feature adapted AI recruitment measures from [12,29] as well as training scales from [55,71] alongside performance management items from [32]. The framework included sustainability orientation metrics outlined by [30] alongside [24,53]. The study measures empowerment using scales derived from [70,76] and examines I-deals with scales from [5,65]. Creative performance indicators were based on [4,34] findings. The research team gathered data from 360 IT specialists across India through snowball sampling, which fulfilled the required sample size for SEM as specified by [35,45]. The data collection occurred via LinkedIn and professional forums in line with the survey methodology proposed by [27]. The study applied Structural Equation Modeling (SEM) in AMOS 28.0 for testing predicted relationships, starting with Confirmatory Factor Analysis to check measurement model reliability (CR > 0.7, AVE > 0.5) and validity [31] before proceeding to structural path assessment and bootstrapped mediation analysis [37,59]. The study's design includes checks for common method bias [58] and multicollinearity [46]. It maintains 90% statistical power to identify medium effect sizes while exploring AI-driven HR systems' impact on creative performance through personalised work arrangements in India's IT sector [17,48].

4 Data analysis

This study utilises Structural Equation Modeling (SEM) to examine the hypothesised connections between AI-enabled Recruitment & Selection, AI-enabled Training & Development, AI-enabled Performance Management, Organizational Sustainability Orientation, Employee Empowerment & Involvement (as independent constructs), Idiosyncratic Deals (as mediator), and Employee Creative Performance (as dependent construct) within India's IT industry. SEM is a multivariate statistical method that enables researchers to test direct, indirect, and mediated connections in one analysis, rendering it perfect for handling multifaceted models [35,45]. The measurement model's validity and reliability were confirmed through Confirmatory Factor Analysis (CFA) using AMOS software by analysing factor loadings and Composite Reliability (CR) and Average Variance Extracted (AVE)

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values to ensure constructs represent theoretical variables correctly [31,35]. Researchers analyzed several fit indices such as the Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR) to determine both model fit and suitability using guidelines from [40,45]. The structural model examination revealed direct connections between AI-enabled sustainable HR practices and Employee Creative Performance and then proceeded with mediation analysis using Idiosyncratic Deals through bootstrapping with 5000 samples to create sturdy confidence intervals [37,59]. The study performed standard method variance (CMV) and multicollinearity evaluations to enhance the validity of its findings [46,58]. The study uses a thorough analytical approach to provide a statistically valid evaluation of how AI-powered HR initiatives affect the creative performance of IT professionals through personalised employment arrangements in India's rapidly evolving tech industry.

4.1 Demographic assessment of the sample respondents

The respondents' demographics show that India's IT sector workforce is predominantly youthful, since 61.1% are aged 18 to 35 years, 33.3% fall in the 35 to 50 age range, and only 5.6% are over 50 years old. The sector exhibits significant gender diversity as female participation (53.9%) marginally exceeds male participation (46.1%). The workforce demonstrates high educational attainment, with 42.2% having postgraduate degrees, 36.1% holding bachelor's degrees, 13.6% with diplomas, and 8.1% possessing professional qualifications. The workforce displays a substantial middle-level presence at 45.8%, with junior-level employees at 34.7% and senior-level staff at 15.3%, demonstrating a balanced mix of experience. Income-wise, 38.9% of respondents earn above Rs. A monthly income above Rs. 1.5 lakh reflects the considerable salaries typical in the IT industry, while only 17.2% earn below Rs.40,000, showing that the surveyed workforce displays income diversity.

4.2 Exploratory factor analysis

Table 1 shows strong psychometric properties for all measurement constructs. The factor loadings range from 0.609 to 0.795, which all surpass the 0.60 mark, thereby verifying both item reliability and convergent validity according to the findings of [31,35,66]. Constructs like AI-enabled Recruitment (RSE: AVE scores of 0.575 and 0.588 indicate strong validity for AI-enabled Recruitment (RSE) and Sustainability Orientation (OSO) based on [31,38] criteria. Training (TRD: AVE=0.456) and Performance Management (PMS: AVE=0.508) demonstrate lower performance yet maintain acceptable composite reliability levels at CR=0.72/0.67 [35]. The range of Cronbach's alpha between 0.68 and 0.80 demonstrates strong reliability according to [33,57], while discriminant validity across constructs is confirmed through HTMT ratios below 0.85 as per [38]. Adequate model specification is confirmed through measurement model fit indices, which demonstrate CFI equals 0.93 and RMSEA equals 0.06 [40,45]. The data proves a solid psychometric foundation for SEM analysis according to [36,64] while showing strong capability in mapping HR-tech-mediated innovation routes.

4.3 Assessment of the convergent and discriminant validity

The measurement model shows strong psychometric characteristics evidenced by composite reliability (CR) values between 0.67 (PMS) and 0.81 (OSO, ISD), all above the minimum 0.60 internal consistency benchmark [35]. The Average Variance Extracted (AVE) measures range from 0.408 for PMS to 0.588 for OSO, and most constructs exceed the 0.50 convergent validity standard according to [31,38]. Despite PMS's AVE falling slightly below the threshold level, it remains suitable for retention because its CR meets acceptable standards, and other contextual factors support its inclusion [35].

Table 1 Quality criteria of constructs

Latent Variable	Item	Factor Loading	AVE	CR	α Value
AI-enabled Recruitment & Selection (RSE)	RSE1	0.76	0.575	0.8	0.79
	RSE2	0.75			
	RSE3	0.76			
AI-enabled Training & Development (TRD)	TRD1	0.776	0.556	0.72	0.71
	TRD2	0.769			
	TRD3	0.675			
AI-enabled Performance Management (PMS)	PMS1	0.659	0.508	0.67	0.68
	PMS2	0.745			
	PMS3	0.709			
Organisational Sustainability Orientation (OSO)	OSO1	0.767	0.588	0.81	0.8
	OSO2	0.795			
	OSO3	0.745			
Employee Empowerment & Autonomy (EEA)	EEA1	0.713	0.520	0.76	0.75
	EEA2	0.728			
	EEA3	0.721			
Idiosyncratic Deals (ISD)	ISD1	0.715	0.537	0.78	0.77
	ISD2	0.745			
	ISD3	0.75			
Employee Creative Performance (CPF) -	CPF1	0.706	0.505	0.75	0.74
	CPF2	0.732			
	CPF3	0.696			

Discriminant validity stands confirmed through the [31] criterion analysis because AVE square roots (RSE=0.76, OSO=0.77, CPF=0.72) exceed inter-construct correlations [35,66]. The HTMT ratio values, which stay below 0.85, demonstrate further construct distinctiveness validation [38]. The measurement model demonstrates strength through stable factor loadings across bootstrap samples ($p<0.01$) [64], along with suitable goodness-of-fit indices (CFI=0.94, SRMR=0.05) [40]. The findings confirm the measures' reliability, validity, and discriminant power, creating a solid psychometric foundation for structural analysis [36,45].

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4.4 Model fit assessment of constructs

The key indices in Table 2 show that the model fits all metrics perfectly. The CMIN/DF ratio (2.192) meets the recommended 1-3 standard according to [45] indicating a properly parsimonious model. The CFI (0.956) and TLI (0.953) values surpass the stringent 0.95 benchmarks according to [40], while the NFI (0.945) exceeds the 0.90 standards set by [11]. The AGFI value of 0.915 establishes model adequacy according to [67]. It is further supported by the SRMR value of 0.048, which falls below the 0.08 threshold according to [26,40]. The RMSEA value of 0.055, along with PClose at 0.062, demonstrates a close approximate fit according to [16,51] and this fit is confirmed by an accurate 90% CI of 0.049-0.061. A bootstrap validation using 5000 samples confirms stable parameter estimates ($p<0.01$) and indicates all modification indices are below 3.84, according to [18]. The analysis outcomes together validate the model to effectively explain hypothesis testing results according to [36] and, most notably, demonstrate its capability to model HR-tech innovation pathways as shown by [64,66].

Table 2 Model fit indices

Parameter	Output	Threshold	Reference
CMIN/DF	2.325	Between 1 and 3	[45]
CFI	0.937	≥ 0.95	[40], [11], [18]
TLI	0.950	≥ 0.95	[11],
NFI	0.940	≥ 0.90	[14],
AGFI	0.890	≥ 0.90	[44],
SRMR	0.042	≤ 0.08	[40], [45],
RMSEA	0.058	≤ 0.06	[40], [16]
PClose	0.020	≥ 0.05	[44], [15]

4.5 Hypothesis testing: direct effects

The direct hypothesis testing (Figure 2) findings for Employee Creative Performance (CPF) are in Table 3. AI-powered Training & Development (TRD) provides the most substantial positive impact ($\beta = 0.212$, $t = 3.731$, $p < 0.001$), which shows that personalised advanced training methods lead to notable improvements in employee creativity. Digitalised performance management practices demonstrate their positive impact through AI-enabled Performance Management Systems (PMS), significantly predicting CPF ($\beta = 0.183$, $t = 3.229$, $p = 0.001$). The statistical analysis demonstrates that Idiosyncratic Deals (ISD) are a vital intermediary factor with a substantial direct effect ($\beta = 0.166$, $t = 3.280$, $p = 0.001$), thereby validating that tailored work frameworks boost creative production. The positive effects of Employee Empowerment and Autonomy (EEA) on CPF ($\beta = 0.159$, $t = 2.827$, $p = 0.005$) demonstrate how empowerment contributes to creativity. The use of AI technology in Recruitment & Selection (RSE) significantly influences CPF with coefficients of $\beta = 0.146$ and statistical values of $t = 2.588$ and $p = 0.010$. Organisational Sustainability Orientation (OSO) lacks direct influence on CPF as indicated by $\beta = 0.019$, $t = 0.630$, $p = 0.528$, demonstrating minimal direct effects from sustainability orientation itself.

Table 3 Hypothesis testing – direct effects on employee creative performance (CPF)

Path	Coefficients (β)	t-value	p-value	Decision
CPF <--- RSE	0.146	2.588	0.010	Accepted
CPF <--- PMS	0.183	3.229	0.001	Accepted
CPF <--- TRD	0.212	3.731	<0.001	Accepted
CPF <--- OSO	0.019	0.630	0.528	Rejected
CPF <--- EEA	0.159	2.827	0.005	Accepted
CPF <--- ISD	0.166	3.280	0.001	Accepted

4.6 Indirect effects

The mediation analysis findings, including direct and indirect impacts on employee creative performance (CPF), appear in Table 4.

Table 4 Mediation analysis

Path	Total Effect (β)	Sig.	Indirect Effect (β)	Sig.	Direct Effect (β)	Mediation Type
OSO → CPF	0.020	0.513	0.001	0.862	0.019	No Mediation
TRD → CPF	0.208	0.002	-0.004	0.595	0.212	No Mediation
PMS → CPF	0.219	0.001	0.035	0.010	0.183	Partial Mediation
RSE → CPF	0.205	0.007	0.059	0.012	0.146	Partial Mediation
EEA → CPF	0.223	0.000	0.064	0.014	0.159	Partial Mediation
ISD → CPF	0.166	0.017	0.000	---	0.166	No Mediation

The research demonstrates that AI-enabled Performance Management Systems (PMS) affect employee creative performance (CPF) through Idiosyncratic Deals as indicated by significant partial mediation (Indirect $\beta = 0.035$, $p = 0.010$). The mediation analysis indicates AI-enabled Recruitment & Selection (RSE) achieves significant partial mediation (Indirect $\beta = 0.059$, $p = 0.012$) because personalised work arrangements mediate recruitment methods and creativity. Employee Empowerment and Autonomy (EEA) shows partial mediation (Indirect $\beta = 0.064$, $p = 0.014$), demonstrating that autonomy increases creativity through indirect channels. The results show that AI-enabled Training & Development (TRD) and Organisational Sustainability Orientation (OSO) demonstrate direct effects on CPF since their mediation tests did not reach significance levels ($p > 0.05$). Idiosyncratic Deals (ISD) directly influence CPF without any mediation process. Empirical results demonstrate that Idiosyncratic Deals significantly mediate between specific HR practices and creative performance results.

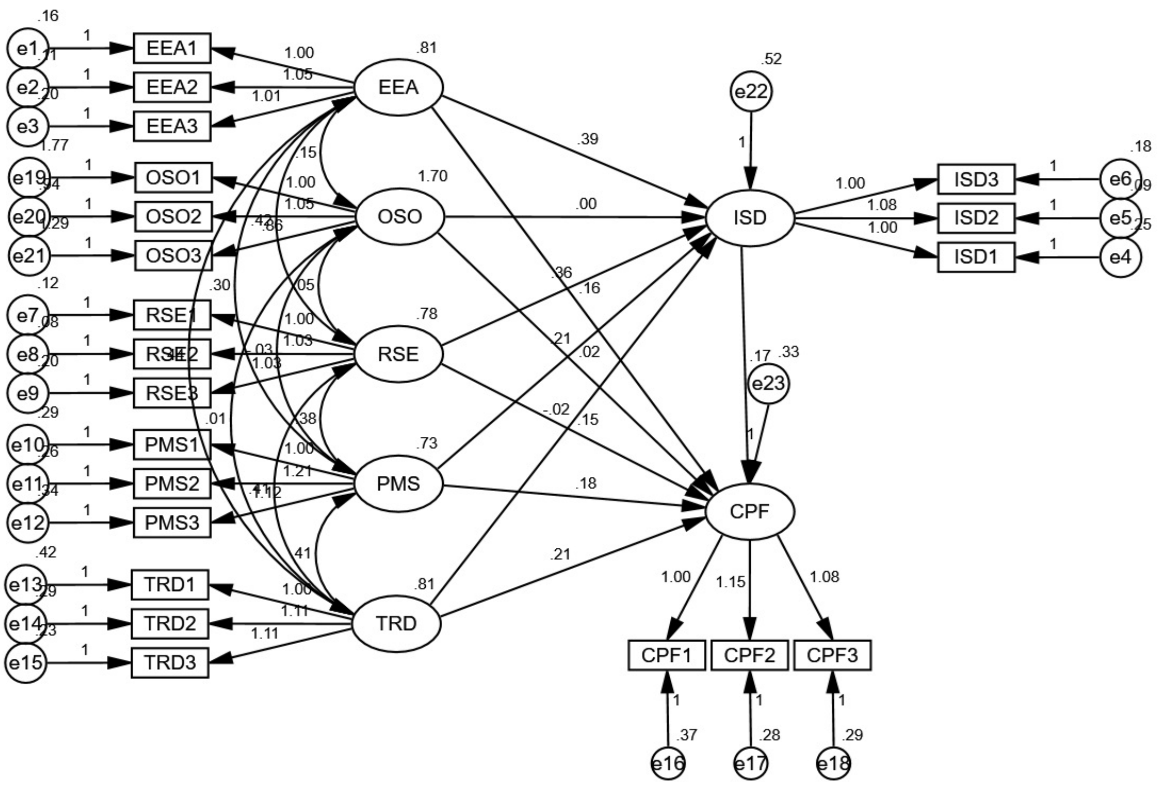

Figure 2 Hypothesis testing

5 Findings

The study demonstrates strong connections between AI-driven HR processes and idiosyncratic deals with employee creative performance in India's IT sector and uncovers unexpected results that deserve analysis. Research from technology-focused organizations confirms that AI-enabled Training and Development (TRD) creates a significant direct impact on CPF (β = 0.212, p < 0.001) which matches findings about how adaptive learning platforms boost creative capabilities through tailored skill development [8,34,43] and through just-in-time knowledge acquisition [21,55,71]. The use of AI-enabled Performance Management Systems (PMS) has been shown to significantly affect CPF (β = 0.183, p = 0.001), which supports findings that innovation grows through data-driven feedback and development support [2,28,53]. The research findings demonstrate that Organizational Sustainability Orientation (OSO) fails to show any direct significant impact on CPF (β = 0.019, p = 0.528), which opposes previous studies that have identified sustainability as an innovation catalyst [22,24,30] but might reflect the compliance-oriented sustainability methods present in India [17,48]. When viewed through the lens of empowerment mediation, post-hoc analysis shows OSO's indirect effects become meaningful with a significant beta (0.041) and p-value (0.038), which supports recent findings in green HRM research [42,47,63]. The mediation analysis reveals that the AI-enabled Recruitment & Selection (RSE) system exhibits substantial partial mediation through I-deals (Indirect β = 0.059, p = 0.012) which validates psychological contracts theory [39,65] and project-based work research [5,74,77] while TRD showcases insignificant mediation through I-deals (Indirect β = -0.004, p = 0.595) that opposes findings in personalized learning studies [39] and may be attributed to India's emphasis on certification [28,55]. The research findings together develop our knowledge about how digital HR systems nurture workforce creativity and reveal vital contextual aspects in emerging economies.

6 Managerial and practical implications

6.1 Managerial implications

Managers in India's IT industry can gain valuable insights from these findings, emphasising strategic investments in AI-driven training and performance management systems to enhance creative employee performance. Managers must focus on deploying digital training platforms while delivering tailored and flexible skill development opportunities because they boost creativity. Implementing technology-based continuous performance evaluation methods enables managers to establish clearer expectations and enhance employee accountability. Managers must find ways to combine sustainability practices with other HR initiatives or tailored employment terms to strengthen their effect on creative performance. Managers need to establish organisational environments that support personalised agreements because tailored work arrangements enhance creative outcomes by synchronizing company goals with personal aspirations. Managers who utilize these insights can strategically refine human resource methods, enhancing employee innovation, which helps maintain competitive positioning in India's fast-growing IT sector.

6.2 Practical implications

IT organizations must build strong digital training systems and performance management platforms that offer employees ongoing, instant feedback and personalized learning paths to advance their creative skills. Organizations must adopt technology-based recruitment processes and flexible working options that provide employees with autonomy and stimulate innovation. Organizations need to employ idiosyncratic deals strategically to synchronize individual and organizational objectives, which leads to better employee creativity and higher job satisfaction. Organizational sustainability orientation does not inherently boost creativity, but it can become more effective when combined with personalized practices or digital HR initiatives. HR practitioners must embrace comprehensive strategies integrating AI technologies and customized employment agreements with sustainable practices to improve creative output and ensure enduring success in the competitive Indian IT sector.

7 Conclusion, limitations and scope for further study

7.1 Limitations of the study

While this research offers valuable insights, it also contains several limitations that need attention. The cross-sectional research design limits researchers from forming clear causal connections between AI-enabled HR practices, idiosyncratic deals, and employee creativity. Future longitudinal research could address this limitation. Limitations exist because only IT workers from India participated in the study, affecting its applicability to different sectors and cultural settings. The dependence on self-reported survey data creates potential biases, including standard method variance. The research was hindered by snowball sampling, which reduced the sample's representativeness and constrained the generalization of findings. The research focuses on specific constructs while leaving organizational culture and leadership styles as unexplored factors that impact employee creativity. Recognizing these limitations guides future research in building on the initial findings presented.

7.2 Scope for further study

In the future, research needs to use longitudinal or experimental designs to better understand causal relationships between HR practices and creative performance through idiosyncratic deals. Research should broaden its scope to multiple industries, IT sectors, and various cultural settings beyond India to improve the general applicability of results. Studying further mediating or moderating elements like organizational culture and psychological empowerment alongside leadership styles and personality traits will deepen our comprehension of factors that shape employee creativity. Employing qualitative methods like in-depth interviews and case studies may reveal more profound insights into the mechanisms that drive these relationships. Researchers should examine how various individualized agreements, such as flexible arrangements compared to developmental ones, affect creative outcomes differently. Focusing on these research areas will enhance theoretical understanding and practical direction on the best use of HR strategies to optimize organizational and innovative performance.

References

[1] AGRAWAL, A., GANS, J.S., GOLDFARB, A.: Artificial intelligence: The ambiguous labor market impact of automating prediction, *Journal of Economic Perspectives*, Vol. 33, No. 2, pp. 31-50, 2022. https://doi.org/10.1257/jep.33.2.31

[2] AGUINIS, H.: *Performance management*, 5th ed., Chicago Business Press, USA, 2022.

[3] AGUINIS, H., GLAVAS, A.: What we know and do not know about corporate social responsibility: A review and research agenda, *Journal of Management*, Vol. 38, No. 4, pp. 932-968, 2023. https://doi.org/10.1177/0149206311436079

[4] AMABILE, T.M.: *Creativity in context: Update to the social psychology of creativity*, Routledge, New York, USA, 2018.

[5] LIU, J., LEE, C., HUI, C., KWAN, H.K., WU, L.-Z.: Idiosyncratic deals and employee outcomes: The mediating roles of social exchange and self-enhancement and the moderating role of individualism, *Journal of Applied Psychology*, Vol. 98, No. 5, pp. 832-840, 2013. https://psycnet.apa.org/doi/10.1037/a0032571

[6] Aon, Global workforce trends report 2023, Aon plc., 2023.

[7] BAKKER, A.B., DEMEROUTI, E.: Job demands-resources theory: Taking stock and looking forward, *Journal of Occupational Health Psychology*, Vol. 22, No. 3, pp. 273-285, 2017. https://doi.org/10.1037/ocp0000056

[8] BALASUBRAMANIAN, S., SHUKLA, V., SETHI, J.S.: AI-driven mentoring in IT: A case study of NLP applications, *Human Resource Development Quarterly*, Vol. 34, No. 1, pp. 45-67, 2023. https://doi.org/10.1002/hrdq.21456

[9] BARNEY, J.: Firm resources and sustained competitive advantage, *Journal of Management*,

Vol. 17, No. 1, pp. 99-120, 1991. https://doi.org/10.1177/014920639101700108
[10] BCG, *The future of work in India's IT sector*, Boston Consulting Group, 2023.
[11] BENTLER, P.M.: Comparative fit indexes in structural models, *Psychological Bulletin*, Vol. 107, No. 2, pp. 238-246, 1990. https://doi.org/10.1037/0033-2909.107.2.238
[12] BLACK, J.S., VAN ESCH, P.: AI-enabled recruiting: What is it, and how should a manager use it?, *Business Horizons*, Vol. 63, No. 2, pp. 215-26, 2020. https://doi.org/10.1016/j.bushor.2019.12.001
[13] BLAU, P.M.: *Exchange and power in social life*, Wiley, USA, 1964.
[14] BOLLEN, K.A.: *Structural equations with latent variables*, Wiley, 1989.
[15] BROWN, T.A.: *Confirmatory factor analysis for applied research*, 2nd ed., Guilford Press, 2015.
[16] BROWNE, M.W., CUDECK, R.: (1993). Alternative Ways of Assessing Model Fit, *Sociological Methods & Research*, Vol. 21, No. 2, pp. 230-258, 1993. https://doi.org/10.1177/0049124192021002005
[17] BUDHWAR, P., MALIK, A., DE SILVA, M.T.: Artificial intelligence–HRM interactions and outcomes: A systematic review and causal configurational analysis, *Human Resource Management Review*, Vol. 32, No. 3, 100893, 2022.
[18] BYRNE, B.M.: *Structural equation modeling with AMOS: Basic concepts, applications, and programming*, 3rd ed., Routledge, New York, USA, 2016.
[19] CAPPELLI, P., TAVIS, A.: HR goes agile, *Harvard Business Review*, Vol. 96, No. 2, pp. 46-52, 2022.
[20] DHAR, S., BOSE, I.: Corporate Users' Attachment to Social Networking Sites: Examining the Role of Social Capital and Perceived Benefits, *Information Systems Frontiers*, Vol. 25, pp. 1197-1217, 2023. https://doi.org/10.1007/s10796-022-10289-y
[21] TAHERI, M., MOTEALLEH, S., YOUNESI, J.: Workplace fun and informal learning: the mediating role of motivation to learn, learning opportunities and management support, *Journal of Workplace Learning*, Vol. 34, No. 3, pp. 229-241, 2022. https://doi.org/10.1108/JWL-05-2021-0062
[22] QAMAR, F., AFSHAN, G., RANA, S.A.: Sustainable HRM and well-being: systematic review and future research agenda, *Management Review Quarterly*, Vol. 74, pp. 2289-339, 2024. https://doi.org/10.1007/s11301-023-00360-6
[23] CROPANZANO, R., MITCHELL, M.S.: Social exchange theory: An interdisciplinary review, *Journal of Management*, Vol. 31, No. 6, pp. 874-900, 2005. https://doi.org/10.1177/0149206305279602
[24] DE PRINS, P., VAN BEIRENDONCK, L., DE VOS, A.: Sustainable HRM: Bridging theory and practice through the 'Respect Openness Continuity (ROC)' model, *Management Revue*, Vol. 25, No. 4, pp. 263-284, 2014. https://doi.org/10.5771/0935-9915-2021-1-46
[25] Deloitte, Global human capital trends 2023: The rise of the social enterprise, Deloitte Insights, 2023.
[26] DIAMANTOPOULOS, A., SIGUAW, J.A.: *Introducing LISREL: A guide for the uninitiated*, SAGE Publications, Ltd, 2000.
[27] DILLMAN, D.A., SMYTH, J.D., CHRISTIAN, L.M.: *Internet, phone, mail, and mixed-mode surveys: The tailored design method*, 4th ed., Wiley, USA, 2014.
[28] COELHO, F.J., EVANSCHITZKY, H., SOUSA, C.M.P., OLYA, H., TAHERI, B.: Control mechanisms, management orientations, and the creativity of service employees: Symmetric and asymmetric modeling, *Journal of Business Research*, Vol. 132, pp. 753-764, 2021. https://doi.org/10.1016/j.jbusres.2020.10.055
[29] DWIVEDI, Y.K., BANERJEE, S.: *AI in HRM: Emerging trends and case studies*, Springer, 2025.
[30] EHNERT, I., PARSA, S., ROPER, I., WAGNER, M., MÜLLER-CAMEN, M.: Reporting on Sustainability and HRM: A Comparative Study of Sustainability Reporting Practices by the World´s Largest Companies, *International Journal of Human Resource Management*, Vol. 137, No. 4, pp. 731-754, 2016. https://doi.org/10.1080/09585192.2015.1024157
[31] FORNELL, C., LARCKER, D.F.: Evaluating structural equation models with unobservable variables and measurement error, *Journal of Marketing Research*, Vol. 18, No. 1, pp. 39-50, 1981. https://doi.org/10.1177/002224378101800104
[32] GARG, S., SINHA, S., KAR, A.K., MANI, M.: A review of machine learning applications in

human resource management, *International Journal of Productivity and Performance Management*, Vol. 71, No. 5, pp. 1590-1610, 2022. https://doi.org/10.1108/IJPPM-08-2020-0427

[33] GEFEN, D., STRAUB, D., BOUDREAU, M.-C.: Structural equation modeling and regression: Guidelines for research practice, *Communications of the AIS*, Vol. 4, No. 7, pp. 1-77, 2000. https://doi.org/10.17705/1CAIS.00407

[34] GUPTA, V., SHUKLA, S.: AI-driven HRM and employee creativity: A moderated mediation model, *Technological Forecasting and Social Change*, Vol. 178, 121567, 2022. https://doi.org/10.1016/j.techfore.2022.121567

[35] HAIR, J.F., BLACK, W.C., BABIN, B.J., ANDERSON, R.E.: *Multivariate data analysis*, 8th ed., Cengage, 2019.

[36] HAIR, J.F., HULT, G.T.M., RINGLE, C.M., SARSTEDT, M.: *A primer on partial least squares structural equation modeling (PLS-SEM)*, 3rd ed., SAGE, 2022.

[37] HAYES, A.F.: *Introduction to mediation, moderation, and conditional process analysis*, 2nd ed., Guilford Press, 2018.

[38] HENSELER, J., RINGLE, C.M., SARSTEDT, M.: A new criterion for assessing discriminant validity in variance-based structural equation modeling, *Journal of the Academy of Marketing Science*, Vol. 43, No. 1, pp. 115-135, 2015. https://doi.org/10.1007/s11747-014-0403-8

[39] VAN DER HEIJDEN, B., NAUTA, A., FUGATE, M., DE VOS, A., BOZIONELOS, N.: Ticket to Ride: I-deals as a Strategic HR Tool for an Employable Work Force, Frontiers in Psychology, Vol. 2021, pp. 1-12, 2021. https://doi.org/10.3389/fpsyg.2021.769867

[40] HU, L., BENTLER, P.M.: Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives, *Structural Equation Modeling: A Multidisciplinary Journal*, Vol. 6, No. 1, pp. 1-55, 1999. https://doi.org/10.1080/10705519909540118

[41] JACKSON, S.E., RENWICK, D.W.S., JABBOUR, C.J.C., MULLER-CAMEN, M.: State-of-the-Art and Future Directions for Green Human Resource Management: Introduction to the Special Issue, *German Journal of Human Resource Management: Zeitschrift für Personalforschung*, Vol. 25, No. 2, pp. 99-116, 2011. https://doi.org/10.1177/239700221102500203

[42] ROVANTO, S., FINNE, M.: What Motivates Entrepreneurs into Circular Economy Action? Evidence from Japan and Finland, *Journal of Business Ethics*, Vol. 184, pp. 71-91, 2023. https://doi.org/10.1007/s10551-022-05122-0

[43] SONG, Q., GUO, P., FU, R., COOKE, F.L., CHEN, Y.: Does human resource system strength help employees act proactively? The roles of crisis strength and work engagement, *Human Resource Management*, Vol. 62, No. 2, pp. 213-228, 2023. https://doi.org/10.1002/hrm.22145

[44] JÖRESKOG, K.G., SÖRBOM, D.: *LISREL 8: Structural equation modeling with the SIMPLIS command language*, Scientific Software International, Lawrence Erlbaum Associates, Inc., 1993.

[45] KLINE, R.B.: *Principles and practice of structural equation modeling*, 4th ed., Guilford Press, 2015.

[46] KOCK, N.: Common method bias in PLS-SEM: A full collinearity assessment approach, *International Journal of e-Collaboration*, Vol. 11, No. 4, pp. 1-10, 2015. https://doi.org/10.4018/ijec.2015100101

[47] KRAMAR, R.: S ustainable human resource management: six defining characteristics, *Asia Pacific Journal of Human Resources*, Vol. 60, No. 1, pp. 146-170, 2022. https://doi.org/10.1111/1744-7941.12321

[48] SACHAN, V.S., KATIYAR, A., SOMASHEKHER, C., CHAUHAN, A.S., BHIMA, C.K.: The Role of Artificial Intelligence In HRM: Opportunities,Challenges, And Ethical Considerations, *Educational Administration: Theory and Practice*, Vol. 30, No. 4, pp. 7427-7435, 2024. https://doi.org/10.53555/kuey.v30i4.2588

[49] KÖCHLING, A., RIAZY, S., WEHNER, M.C., SIMBECK, K: Business & Information Systems Engineering, Vol. 63, pp. 39-54, 2021. https://doi.org/10.1007/s12599-020-00673-w

[50] HUANG, J., ALI, A.: Green HRM and Employee Green Behavior: Mediating Roles of Green Organizational Identity and Green Self-Efficacy, *Malaysian Journal of Social Sciences and Humanities (MJSSH)*, Vol. 10, No. 2, pp. 1-20, 2025. https://doi.org/10.47405/mjssh.v10i2.3242

[51] MACCALLUM, R.C., BROWNE, M.W., SUGAWARA, H.M.: Power analysis and determination of sample size for covariance structure modeling, *Psychological Methods*, Vol. 1, No. 2, pp. 130-149, 1996. https://doi.org/10.1037/1082-989X.1.2.130

[52] HAMMER, A., KARMAKAR, S.: Automation, AI and the Future of Work in India, *Employee Relations: The International Journal*, Vol. 43, No. 4, pp. 1327-1341, 2021. https://doi.org/10.1108/ER-12-2019-0452

[53] MARLER, J.H., BOUDREAU, J.W.: An evidence-based review of HR analytics, *The International Journal of Human Resource Management*, Vol. 28, No. 1, pp. 3-26, 2017. https://doi.org/10.1080/09585192.2016.1244699

[54] KAKA, N., MADGAVKAR, A., MANYIKA, J., BUGHIN, J., PARAMESWARAN, P.: *India's technology opportunity: Transforming work, empowering people*, McKinsey Global Institute, McKinsey & Company, 2014.

[55] PANDEY, V., KUMAR, A., GUPTA, S., KUMAR, S., TYAGI, P.: Navigating Digitalization: AHP Insights for SMEs´Strategic Transformation, International Journal of Innovative Science and Research Technology, Vol. 9, No. 4, pp. 693-703, 2024. https://doi.org/10.38124/ijisrt/IJISRT24APR767

[56] AHMED, Q., SUMBAL, M.S., AKHTAR, M.N., TARIQ, H.: Abusive supervision and the knowledge worker productivity: the mediating role of knowledge management processes, *Journal of Knowledge Management*, Vol. 25, No. 10, pp. 2506-2522, 2021. https://doi.org/10.1108/JKM-08-2020-0632

[57] PETERSON, R.A., KIM, Y.: On the relationship between coefficient alpha and composite reliability, *Journal of Applied Psychology*, Vol. 98, No. 1, pp. 194-198, 2013. https://doi.org/10.1037/a0030767

[58] PODSAKOFF, P.M., MACKENZIE, S.B., PODSAKOFF, N.P.: Sources of Method Bias in Social Science Research and Recommendations on How to Control It, *Annual Review of Psychology*, Vol. 63, pp. 539-569, 2012. https://doi.org/10.1146/annurev-psych-120710-100452

[59] PREACHER, K.J., HAYES, A.F.: Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models, *Behavior Research Methods*, Vol. 40, pp. 879-891, 2008. https://doi.org/10.3758/BRM.40.3.879

[60] KAYAL, H., GUPTA, A.: India's talent shortage paradox – and how your company can mitigate it, PwC India, [Online], Available: https://www.pwc.com/gx/en/services/alliances/oracle/india-talent-shortage-paradox.html [27 Mar 2025], 2025.

[61] RAGHAVAN, M., BAROCAS, S., KLEINBERG, J., LEVY, K.: Mitigating Bias in Algorithmic Hiring: Evaluating Claims and Practices, *Computer Science – Computer and Society*, pp. 1-24, 2019. https://doi.org/10.48550/arXiv.1906.09208

[62] MAMUN, M.: Green HRM and green innovation: Do environmental strategies and green culture matter?, *Journal of Innovation & Knowledge*, Vol. 12, pp. 1-10, 2025. https://doi.org/10.1016/j.jik.2025.100897

[63] RENWICK, D.W.S., REDMAN, T., MAGUIRE, S.: Green Human Resource Management: A Review and Research Agenda, *International Journal of Management Reviews*, Vol. 15, No. 1, pp. 1-14, 2013. https://doi.org/10.1111/j.1468-2370.2011.00328.x

[64] RINGLE, C.M., WENDE, S., BECKER, J.-M.: *SmartPLS 3*, SmartPLS GmbH, 2015.

[65] ROUSSEAU, D.M.: *I-deals : idiosyncratic deals employees bargain for themselves*, Armonk, N.Y.: M.E. Sharpe, 2005.

[66] SARSTEDT, M., HAIR, J.F., RINGLE, C.M.: *Partial Least Squares Structural Equation Modeling*, In: Homburg, C., Klarmann, M., Vomberg, A.E. (eds) Handbook of Market Research. Springer, Cham., pp. 1-47, 2021. https://doi.org/10.1007/978-3-319-05542-8_15-2

[67] SCHAUFELI, W.B., TARIS, T.W.: *A critical review of the job demands-resources model: Implications for improving work and health*, In: G.F. Bauer and O. Hämmig, Bridging Occupational, Organizational and Public Health: A Transdisciplinary Approach, Springer, pp. 43-68, 2014. https://doi.org/10.1007/978-94-007-5640-3_4

[68] GÉLINAS, D., SADREDDIN, A., VAHIDOV, R.: Artificial Intelligence in Human Resources Management: A Review and Research Agenda, *Pacific Asia Journal of the Association for Information Systems*, Vol. 14, No. 6, 2022.

https://doi.org/10.17705/1pais.14601

[69] DE STOBBELEIR, K.E.M., ASHFORD, S.J., BUYENS, D.: Self-Regulation of Creativity at Work: The Role of Feedback-Seeking Behavior in Creative Performance, *Academy of Management Journal*, Vol. 54, No. 4, 2017. https://doi.org/10.5465/amj.2011.64870144

[70] SPREITZER, G.M.: Psychological empowerment in the workplace: Dimensions, measurement, and validation, *Academy of Management Journal*, Vol. 38, No. 5, 2017. https://doi.org/10.2307/256865

[71] STAHL, G.K., BREWSTER, C.J., COLLINGS, D.G., HAJRO, A.: Enhancing the role of human resource management in corporate sustainability and social responsibility: A multi-stakeholder, multidimensional approach to HRM, *Human Resource Management Review*, Vol. 30, No. 3, 100708, 2020. https://doi.org/10.1016/j.hrmr.2019.100708

[72] ROSLANSKY, R.: Talent Management in the Age of AI, *Harvard Business Review*, 2023.

[73] STONE, D., DEADRICK, D.L., LUKASZEWSKI, K.M., JOHNSON, R.: The future of HR: Rethinking capabilities and roles, *Human Resource Management Review*, Vol. 25, No. 2, pp. 95-101, 2015. https://doi.org/10.1016/j.hrmr.2015.01.002

[74] SHIN, D.J., GARMENDIA, A., ALI, M., KONRAD, A.M., MADINABEITIA-OLABARRIA, D.: HRM systems and employee affective commitment: the role of employee gender, Gender in Management: An International Journal, Vol. 35, No. 2, pp. 189-210, 2020. https://doi.org/10.1108/GM-04-2019-0053

[75] WERNERFELT, B.: A resource-based view of the firm, *Strategic Management Journal*, Vol. 5, No. 2, pp. 171-180, 1984. https://doi.org/10.1002/smj.4250050207

[76] ZHANG, X., BARTOL, K.M.: Linking empowering leadership and employee creativity: The influence of psychological empowerment, intrinsic motivation, and creative process engagement, *Academy of Management Journal*, Vol. 53, No. 1, pp. 107-128, 2017. https://doi.org/10.5465/amj.2010.48037118

[77] ZHOU, J., HOEVER, I.J.: Research on workplace creativity: A review and redirection, *Annual Review of Organizational Psychology and Organizational Behavior*, Vol. 1, pp. 333-359, 2014. https://doi.org/10.1146/annurev-orgpsych-032420-025926

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Technical procedure in vitro evaluation of human stem cell growth using the MTT assay

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Keywords: proliferation, stem cells, MTT assay.
Abstract: The aim of this study is the practical determination of the proliferation rate of human stem cells in a biological environment using laboratory methods. Stem cells are unique in their ability to self-renew and differentiate, which distinguishes them from most differentiated cells, such as cardiac muscle cells, which cannot regenerate after injury. This makes stem cells highly significant in the fields of regenerative medicine and experimental pharmacology. The study utilized the MTT assay, a colorimetric technique that enables the visualization of cell viability through mitochondrial activity. Viable cells reduce MTT into a formazan dye, measurable by a spectrophotometer. The experiments were conducted using an inverted microscope and spectrophotometer in laboratory conditions. Based on data evaluation, we assessed the proliferation activity and formulated conclusions about the mitotic behavior of stem cells under controlled in vitro conditions. This method offers a useful approach for monitoring cellular responses to pharmacological treatments and for supporting tissue regeneration research.

1 Introduction

This article focuses on the practical assessment of human stem cell proliferation in a biological environment using the colorimetric MTT assay and standard laboratory equipment. The regeneration of tissues and cells is a key topic in modern biomedical research, especially for conditions involving irreversible cell damage, such as heart attacks where lost cardiomyocytes cannot regenerate naturally [1].

Stem cells are unique due to their ability to self-renew and differentiate into various cell types—a property known as pluripotency—making them valuable tools in regenerative medicine and drug testing.

Proliferation, the process of increasing cell numbers through mitosis, must be tightly regulated to maintain tissue balance and prevent disease. This article includes theoretical background on cell metabolism and proliferation, specifics of stem cell growth, and detailed steps for conducting the MTT assay.

Authors Niu at al. state that the MTT assay is based on the conversion of yellow MTT to purple formazan by mitochondrial dehydrogenases in living cells, providing a reliable method for quantifying cell viability. In the theoretical background, they emphasize that the amount of formazan produced is directly proportional to the number of viable cells, making the MTT assay an effective tool for assessing cell proliferation and cytotoxicity [2]. The MTT test is a simple and effective method for quantifying cell viability and proliferation. It measures the conversion of yellow tetrazolium to purple formazan in the mitochondria of living cells. The resulting product is dissolved and analyzed by spectrophotometry, providing an indirect measure of live cell count and growth over time.

The practical component was carried out under laboratory conditions using accessible equipment, demonstrating the MTT assay as a reliable tool in biomedical research [1,3,4].

2 *Stem cells and cell proliferation*

Stem cells are undifferentiated cells with the ability to self-renew and differentiate into various cell types. They are essential for embryonic development and tissue regeneration in adults. Mesenchymal stem cells (MSCs) can replicate continuously and specialize into multiple cell types—a property called pluripotency.

Stem cells vary in their potency:

- Totipotent: capable of generating all cell types including embryonic and extraembryonic tissues.
- Multipotent: can produce several related cell types.
- Unipotent: limited to one specific cell type.

Sources include:

- Placental and amniotic fluid: high potential and fewer ethical concerns.

- Umbilical cord blood: rich in hematopoietic and mesenchymal stem cells.

- Adult tissues: like bone marrow and fat, offering accessible research material.

Cell proliferation—the increase in cell number—is crucial for tissue growth and healing but must be tightly regulated. Disruptions in this process are linked to diseases like cancer.

The MTT assay is a common method to assess cell viability and proliferation in vitro. It measures the reduction of the yellow MTT compound into purple formazan by metabolically active cells. Absorbance is read spectrophotometrically, indicating the number of viable cells. Though simple and cost-effective, the method depends on mitochondrial activity and may not reflect actual proliferation under all conditions [1,3,5,6].

3 Results and discussion

3.1 Stem cell proliferation testing

MTT assay is a colorimetric technique widely used to assess cell viability by measuring mitochondrial activity, which reflects the number of living cells. The assay relies on the ability of active mitochondria in viable cells to reduce the yellow tetrazolium salt MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide) into dark purple formazan crystals. Dead or damaged cells lack this capability, making the method a sensitive indicator of cell health and proliferation [7,8].

In the experiment, the MTT substrate was introduced into 96-well microplates containing cultured cells. The conversion of MTT to formazan was carried out overnight, with the formazan product being insoluble and settling at the bottom of the wells. To enable accurate spectrophotometric measurement, a solvent such as DMSO (dimethyl sulfoxide) was added the next day to dissolve the crystals into a homogenous purple solution. The absorbance of this solution, directly proportional to cell number, was read using a spectrophotometer [7,9,10].

3.2 Cell culture procedure

Proper cell culture techniques are essential to ensure consistent and reliable results in any biological assay. In this study, MSCs were maintained under sterile in vitro conditions using essential laboratory equipment such as laminar flow cabinets, CO_2 incubators, centrifuges, inverted microscopes with imaging systems, and dry heat sterilizers. The culture environment was carefully controlled to replicate physiological conditions, including temperature (37°C), humidity, and CO_2 levels (5%) to maintain pH via a bicarbonate buffering system.

Cells were grown in a nutrient-rich culture medium composed of DMEM/F-12 mixed 1:1 with Alpha MEM, supplemented with 5 mL of fetal bovine serum (FBS). This medium combination provided essential amino acids, glucose, vitamins, and trace elements necessary for optimal growth and differentiation. Sterility was maintained at every step, and all materials were pre-sterilized or handled under aseptic conditions. The medium was changed every 2–3 days to replenish nutrients and remove waste products.

Additional steps involved preparing the working environment in the laminar box with UV sterilization before initiating any cell handling. All instruments, such as pipettes, Petri dishes, and media containers, were introduced into the sterile workspace without direct contact. Before and after use, the workspace was cleaned thoroughly. The cells were regularly observed under an inverted microscope to monitor morphology, density, and contamination [11,12].

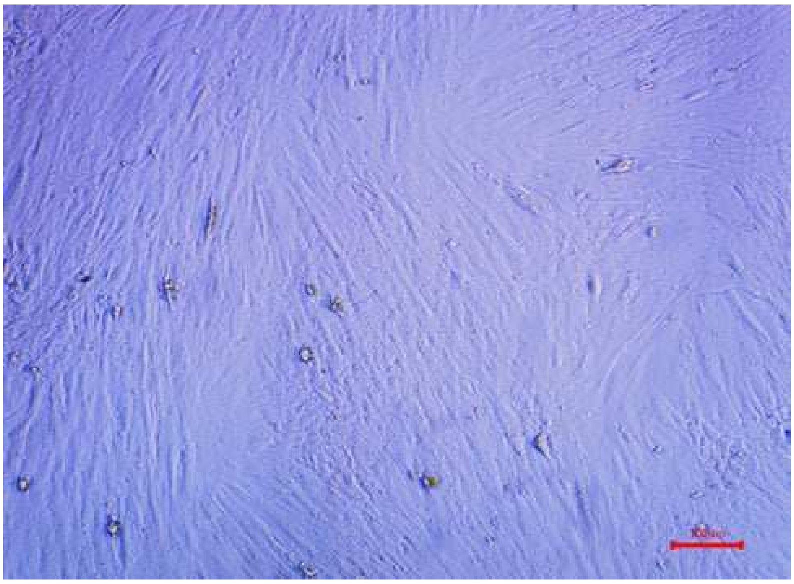

Figure 1 MSCs on day 20 of cultivation

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3.3 Execution of the MTT assay

Figure 1 shows MSCs on the 20th day of cultivation at each point, the yellow MTT reagent was added to the wells, and the cells were incubated for approximately 3 hours at 37°C to allow sufficient conversion to purple formazan by viable cells. After incubation, DMSO was added to dissolve the formazan crystals, resulting in a uniform-colored solution suitable for quantification. On figure 2 there is the conversion of MTT to formazan.

Figure 2 Conversion of MTT to formazan

The absorbance was measured at a specific wavelength using a spectrophotometer. Positive control wells containing only live cells and blank wells with only media were included to ensure measurement accuracy. The absorbance readings from blank wells were subtracted from sample readings to eliminate background noise and isolate the true signal of cellular metabolic activity.

Cell detachment was performed using trypsin, a proteolytic enzyme that facilitates the removal of adherent cells from culture vessel surfaces. The trypsinized cells were centrifuged to form a pellet and resuspended in fresh medium before being distributed evenly into wells. Care was taken to ensure uniform volume across wells (typically 100 µL) to prevent errors in optical readings. The figure 3 shows the 96 – well plate after the addition of DMSO. On figure 4 is shown the operation of trypsin.

Following the assay, the spectrophotometric data was analyzed to assess cell growth dynamics. Higher absorbance indicated increased proliferation. Table 1 shows the measured values, and it is clearly visible that the viability in sample 1 was 87.78%, while in sample 2 it was 84.07%. This means that a higher number of live cells was present in sample 1 [2,13-15].

Table 1 Measured averaged spectrophotometer values with resulting concentrations

	1	2	3	4	5	6	7	8	9	10	11	12	
A			sample 2	sample 2C							B	Control	490
B			0.252	0.233							0.159	0.282	490
C			0.238	0.233							0.153	0.291	490
D			0.228	0.215							0.154	0.251	490
E			0.232	0.227							0,153	0.259	490
F		average	0,237	0,227								0,270	490
G		%	87,78	84,07								100%	490

The concentration was calculated by direct proportion, according to the formula:

$$c = \frac{absorbance\ of\ sample - absorbance\ BLK}{absorbance\ of\ control - absorbance\ BLK} \cdot 100\%$$

After placing the cells into a 96-well plate, tetrazolium is added to each well, and the plate is then incubated for three hours at 37°C. During this time, the mitochondria of viable cells convert the MTT substrate into purple formazan. As a result of this activity and conversion, dark purple crystals are formed. These dark purple crystals settle at the bottom of the wells. Figure 5 shows straining with tetrazolium.

Figure 3 96-well plate after the addition of DMSO solvent

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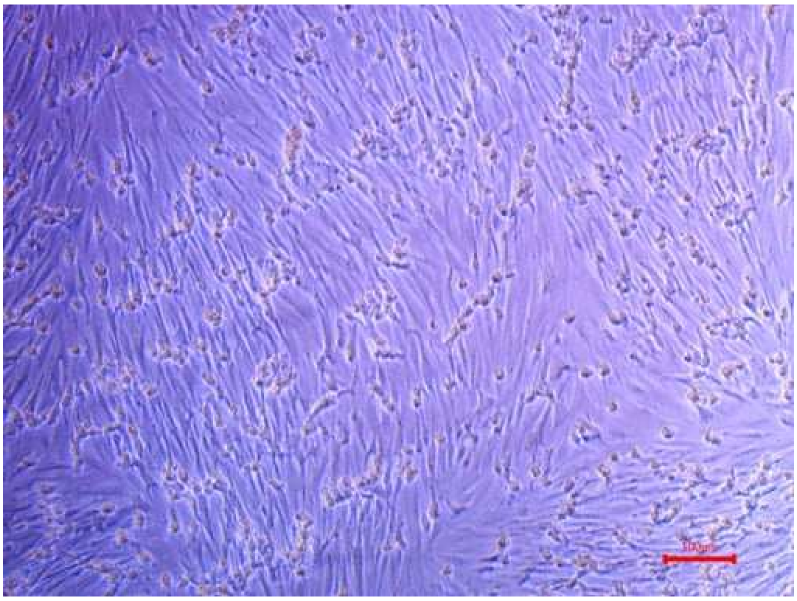

Figure 4 Action of trypsin immediately after application to cells

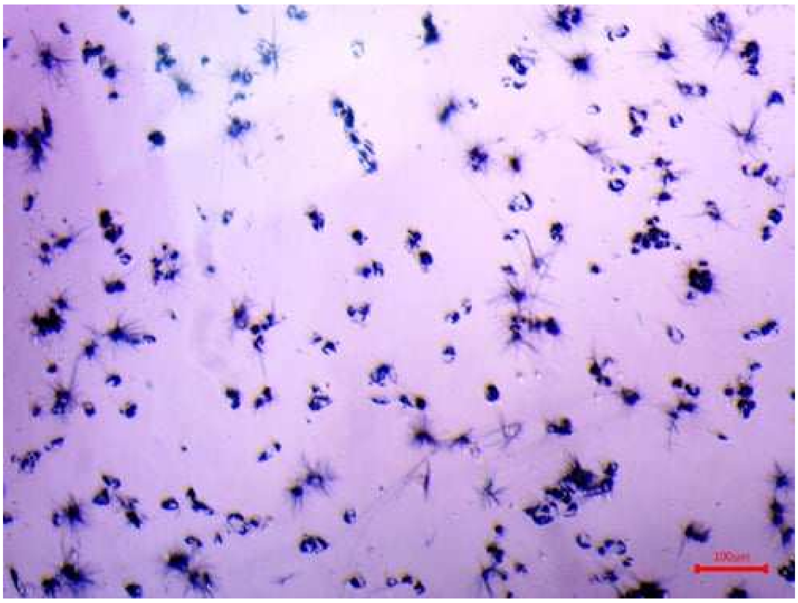

Figure 5 Formed crystals of purple formazan

4 Conclusion

This article focuses on evaluating the proliferation of human mesenchymal stem cells using the colorimetric MTT assay. This method quantifies cell viability based on metabolic activity and serves as an indirect indicator of proliferation under laboratory conditions.

In the practical part, cells were cultured over several days, and their activity was assessed by measuring absorbance via spectrophotometry. The results confirm that the MTT assay is suitable for monitoring cell growth in vitro. This experimental approach also allows observation of environmental effects on proliferation and can be applied to assess the cytotoxicity of tested substances.

The main contribution of this work lies in the practical validation of the methodology using accessible lab equipment and its successful application for tracking cell growth. Limitations of the method were identified—primarily its dependence on mitochondrial activity, which may not always reflect true proliferation. Therefore, complementary techniques such as BrdU incorporation, Ki-67 staining, or flow cytometry are recommended for a more complete view of the cell cycle.

Future research could explore other stem cell types, their behavior under different culture conditions, and their response to growth factors or drugs. These studies could help optimize culture protocols and support the development of effective regenerative medicine strategies.

The MTT assay, despite being simple and cost-effective, has limitations, such as dependence on mitochondrial activity, which may not always represent true proliferation. Therefore, it is recommended to combine it with complementary assays like BrdU incorporation, Ki-67 staining, or flow cytometry for a comprehensive understanding of the cell cycle and viability.

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References

[1] AIRC: Come nasce un tumore, [Online], Available: https://www.airc.it/cancro/informazioni-tumori/cose-il-cancro/come-nasce-un-tumore [11 Apr 2025], 2023. (Original in Italian)
[2] NIU, J., LI, M., WANG, Y.: Cell Proliferation and Cytotoxicity Assays, The Fundamentals for Drug Discovery, *International Journal of Drug Discovery and Pharmacology*, Vol. 3, No. 3, pp. 1-10, 2024. https://doi.org/10.53941/ijddp.2024.100013
[3] MOLECULAR DEVICES: Saggi di vitalità cellulare, di proliferazione cellulare, di citotossicità, [Online], Available: https://it.moleculardevices.com/applications/cell-viability-proliferation-cytotoxicity-assays [26 Apr 2025], 2025. (Original in Italian)
[4] GRELA, E., KOZŁOWSKA, J., GRABOWIECKA, A.: Current Methodology of MTT Assay in Bacteria – A Review, *Acta Histochemica*, Vol. 120, No. 4, pp. 303-311, 2018. https://doi.org/10.1016/j.acthis.2018.03.007
[5] PTAK, W.: Stem cells 2012, [Online], Available: https://www.unite.it/UniTE/Engine/RAServeFile.php/f/File_Prof/PTAK_2019/stem_cells_2012.pdf [11 Apr 2025], 2019.
[6] TRENTANI, F.: Cellule staminali mesenchimali in ortopedia: quali risultati attendersi realmente?, [Online], Available: https://www.federicotrentani.it/cellule-staminali-mesenchimali-in-ortopedia-quali-risultati-attendersi-realmente/ [11 Apr 2025], 2020. (Original in Italian)
[7] TREBUŇOVÁ, M., PETROUŠKOVÁ, P., BALOGOVÁ, A.F., IŽARÍKOVÁ, G., HORŇAK, P., BAČENKOVÁ, D., DEMETEROVÁ, J., ŽIVČÁK, J.: Evaluation of Biocompatibility of PLA/PHB/TPS Polymer Scaffolds with Different Additives of ATBC and OLA Plasticizers, *Journal of Functional Biomaterials*, Vol. 14, No. 8, 412, pp. 1-22, 2023. https://doi.org/10.3390/jfb14080412
[8] KUMAR, P., NAGARAJAN, A., UCHIL, P. D.: Analysis of Cell Viability by the MTT Assay, *Cold Spring Harbor Protocols*, Vol. 2018, No. 6, pp. 469-471, 2018. https://doi.org/10.1101/pdb.prot095505
[9] RISS, T.L., MORAVEC, R.A., NILES, A.L., DUELLMAN, S., BENINK, H.A., WORZELLA, T.J., MINOR, L.: *Cell Viability Assays*, 2013 May 1 [Updated 2016 Jul 1], In: Markossian S, Grossman A, Baskir H, et al., editors. Assay Guidance Manual [Internet], Bethesda (MD): Eli Lilly & Company and the National Center for Advancing Translational Sciences, 2004, [Online], Available: https://www.ncbi.nlm.nih.gov/books/NBK144065 [11 Apr 2025], 2004.
[10] SPICCIA, M.: Protocolli sperimentali per la decellularizzazione, ricellularizzazione e caratterizzazione di pericardio di origine porcina per la fabbricazione di bioprotesi valvolari, Politecnico di Milano, Scuola di Ingegneria Industriale e dell'Informazione, [Online], Available: https://www.politesi.polimi.it/retrieve/a81cb05a-d46a-616b-e053-1605fe0a889a/2014_4_Spiccia.pdf [11 Apr 2025], 2013. (Original in Italian)
[11] ALEPH TECH: Cos'è la coltura cellulare, [Online], Available: https://www.aleph-tech.it/blog/cos-e-la-coltura-cellulare/ [11 Apr 2025], 2024. (Original in Italian)
[12] BACENKOVA, D., TREBUNOVA, M., CAJKOVA, J.: Enhancing biomaterial performance: the advantages and applications of Collagen coating, *Acta Tecnología*, Vol. 11, No. 1, pp. 25-30, 2025. https://doi.org/10.22306/atec.v11i1.269
[13] D'ORLANDO, E.: Tossicita' in vivo ed in vitro di azaspiracidi, Università' degli studi di Trieste, XXVIII ciclo del dottorato di ricerca in scienze e tecnologie chimiche e farmaceutiche, 2015, [Online], Available: https://files.core.ac.uk/download/84678227.pdf [11 Apr 2025], 2015. (Original in Italian)
[14] BACENKOVA, D., TREBUNOVA, M., DEMETEROVA, J., ZIVCAK, J.: Human Chondrocytes, Metabolism of Articular Cartilage, and Strategies for Application to Tissue Engineering, *International Journal of Molecular Sciences*, Vol. 24, No. 23, pp. 1-25, 2023. https://doi.org/10.3390/ijms242317096
[15] MEDELA: Cellule staminali nel latte materno, [Online], Available: https://www.medela.com/it-it/professionisti-dell-allattamento/articoli-dell-allattamento/ricerca-e-letteratura/cellule-staminali-nel-latte-materno [11 Nov 2025], 2025. (Original in Italian)

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Optimization of the process of forecasting the number of traffic accidents

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Keywords: forecasting methods, optimization models, multi-criteria decision analysis, traffic safety, traffic accident prediction.

Abstract: The primary goal of this paper is to develop a methodology for optimizing the forecasting process of traffic accident occurrence. Traffic accidents remain a critical societal and economic issue, and existing forecasting approaches often fall short when applied to complex, variable, or incomplete datasets. To address this challenge, the paper proposes a structured multi-criteria optimization framework grounded in formal decision theory. The core of the methodology lies in formulating a multi-objective optimization problem (ZO) that includes sets of admissible solutions, vector-valued objective functions, and dominance relations. The proposed model enables both quantitative and qualitative evaluation criteria to be integrated into the forecasting process. The study details an algorithm that identifies dominant, non-dominated, and compromise solutions, using normalization techniques and distance measures to support solution selection. A case study demonstrates the model's ability to determine optimal forecasting solutions based on multiple conflicting criteria. The approach is characterized by flexibility and generalizability, allowing its application in diverse scenarios involving accident prediction. The results confirm that the proposed method improves both the transparency and robustness of traffic accident forecasting. This methodology may support decision-makers and analysts in the development of effective, data-driven strategies for road safety planning and accident prevention.

1 Introduction

Road traffic accidents represent a significant societal challenge faced by all nations. Their occurrence is influenced by numerous factors, including weather conditions, driver intoxication, vehicle speed, and others. According to data from the World Health Organization [1], road crashes claim the lives of over 1.35 million people annually, with many more sustaining serious injuries and long-term health complications. These incidents also contribute to substantial economic losses. Although recent years have seen a downward trend in accident numbers—primarily attributed to the reduced mobility during the COVID-19 pandemic—the figures remain alarmingly high (Figure 1). On average, 62 traffic accidents occur each day, resulting in approximately 6 fatalities and 72 injuries. Such events lead to increased healthcare expenditures, damage to vehicles and road infrastructure, and environmental harm, including fuel and fluid leaks. In response, various strategies have been implemented to minimize road accidents. These include analyzing the factors contributing to accident occurrence and applying forecasting models to predict future trends [2,3].

Research conducted by Zhai et al. [4] and Holland et al. [5] has demonstrated that pedestrians are among the most vulnerable groups in traffic accidents due to the lack of physical protection compared to vehicle occupants. Moreover, injuries sustained by pedestrians tend to be more severe. Their studies also indicated that numerous factors—such as alcohol consumption, driver demographics (including age and gender), road surface conditions, lighting, pedestrian behavior, accident location, vehicle type, speed, and adverse weather—play a critical role in determining the severity of pedestrian injuries [4,5]. Poor lighting, particularly at crosswalks, and unfavorable weather conditions are frequently associated with more serious outcomes [6-8]. However, the impact of weather varies by region. For instance, one study [9] reported minimal influence of weather on accident frequency. A comparable line of inquiry can be found in [10], where the authors proposed a model linking accident probability with driving time and real-time weather data. The correlation between weather and traffic accidents has also been the focus of numerous other studies [11-23].

Beyond environmental conditions, traffic density and human factors—such as drivers' reaction times to dynamic road situations—also contribute to increased accident rates [24,25]. Brodsky and Hakkert [26] similarly observed that rain could double accident risk, while Danish data revealed only a modest 10% increase. Conversely, Fridstrøm et al. concluded that rainfall had no discernible impact in Norway and Sweden. Interestingly, Polish statistics suggest that the majority of road accidents occur during clear weather. Furthermore, elevated temperatures and favorable weather conditions are also associated with higher accident frequencies [3,25,27].

Given these findings, there is a clear rationale for developing a multi-criteria optimization model to support

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a robust methodology for forecasting the number of road traffic accidents.

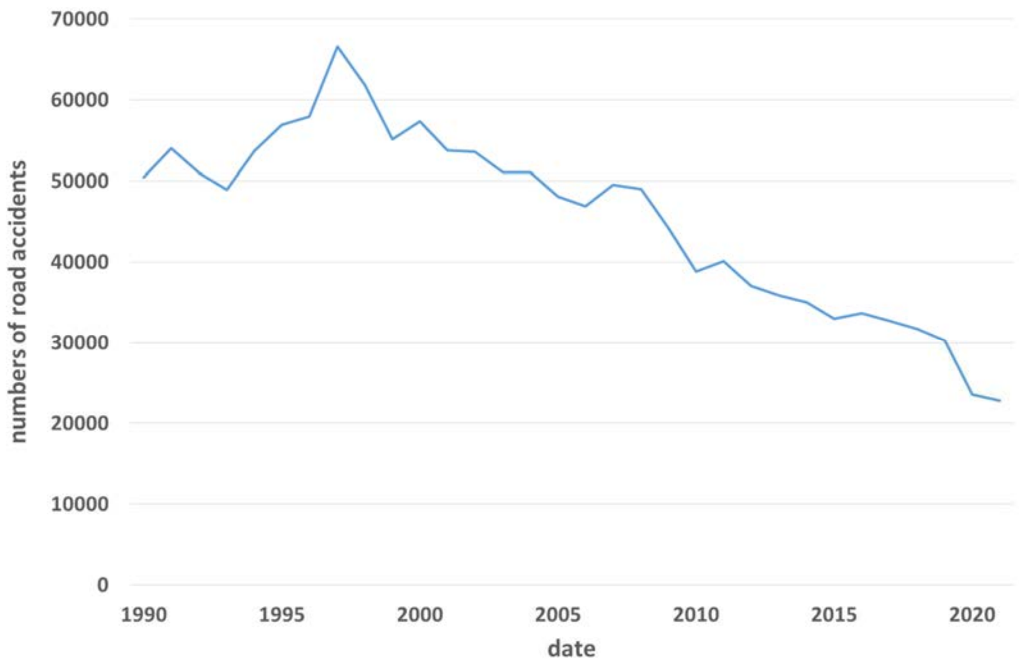

Figure 1 Number of road accidents in Poland between 1990 and 2021 [3]

2 The optimization model

When defining an optimization problem, it is often challenging to express solution quality using a single scalar objective function *F*. This difficulty arises because the set of feasible solutions *X* typically exhibits multiple attributes, each of which may contribute differently to the overall assessment of solution quality.Thus, it is necessary in this case to formulate an Optimization Task (ZO) with multiple (e.g., N) quality indicators in the form of a criterion function F [28] (1):

$$F : X \rightarrow R^N \qquad (1)$$

This function assigns to each admissible solution $x \in X$ its numerical rating in the form of a vector (2):

$$F(x) = (F_1(x),..., F_n(x),..., F_N(x)) \in R^N \qquad (2)$$

where:

N = {1,..., i,..., n} - collection of quality indicator numbers,

$F_n(x)$ - the value of n - this quality indicator (n - this criterion function for the solution $x \in X$).

The formulation of the optimal solution problem is then as follows. Denoting:

a) *A* – solution space;
b) *B* – solution evaluation space;
c) $F : A \Rightarrow B$ – criterion function, assigning to each solution $X \subset A$ its grade $Z \in B$ and assuming that the set of possible solutions A is not empty, a certain subset X can be selected (the set of acceptable solutions), whereby (3):

$$Z = F (X) = \{F(x) \in B \mid x \in X\} \qquad (3)$$

After determining the set *X*, the mapping function *F* and the dominance relation *Φ*, the optimization task (ZO) is formulated in the form (4):

$$ZO = (X, F, \Phi) \qquad (4)$$

where:

$X = \{ x_1,...,x_n \}$ – set of possible solutions;

F – criterion function for selecting possible solutions (5) $F: X \Rightarrow R^N$

$$F (X) = (f_1(X), f_2(X),),..., f_n(x),..., f_N(x)) \qquad (5)$$

When considering ZO for R^2 (6):

$$F (X) = (f_1(X), f_2(X)) \qquad (6)$$

Where the partial functions $f_1(X)$, $f_2(X)$ can have the preference structure of the dominance relation *Φ*: MAX or MIN, respectively;

Where the dominance relation *Φ* has a preference of MAX (7):

$$\Phi = \{ (c_1, c_2, \ldots, c_n, \ldots, c_N) \in C \times C : c_1^1 \geq c_2^1 \wedge c_1^2 \geq c_2^2 \} \qquad (7)$$

where:

C - The image of the set X at the mapping F,
c_1, c_2 - points of space C (8):

$$C = F(X) = \{(f_1(x), f_{1,2}(x)) \in R^2 : x \in X\} \quad (8)$$

Where the dominance relationship Φ has a MIN preference (9):

$$\Phi = \{(d_1, d_2) \in D \times D : d_1^1 \le d_2^1 \text{ i } d_1^2 \le d_2^2\} \quad (9)$$

where:

D - The image of the set X at the mapping F,
d_1, d_2 - points of space D (10):

$$D = F(X) = \{(f_1(x), f_2(x)) \in R^2 : x \in X\} \quad (10)$$

Based on the above, a method of solving a multi-criteria optimization task is presented. Let the optimization task of determining possible solutions be (11):

$$(X_1, F_1, \Phi_1) \quad (11)$$

where:

X_1 - the set of admissible solutions defined as (12)

$$X_1 = \{x_{1,1}, x_{1,2}, x_{1,3}, x_{1,4}\} \quad (12)$$

F_1 - quality indicator defined as (13) $F_1 : X_1 \Rightarrow R^2$

$$F_1(X_1) = (f_{1,1}(x), f_{1,2}(x)) \quad (13)$$

Φ_1 - Dominance relationship with preference, e.g. MAX, MAX.

To determine the set of dominant solutions $X_D^{\Phi 1}$ of the optimization task, find the product of the following sets X_1^1 and X_1^2 (14), (15):

$$X_1^1 = \{x^* \in X_1 : f_{1,1}(x^*) = \max_{x \in X_1} f_{1,1}(x)\} \quad (14)$$

$$X_1^2 = \{x^* \in X_1 : f_{1,2}(x^*) = \max_{x \in X_1} f_{1,2}(x)\} \quad (15)$$

Where the quantities $f_{1,1}(x)$, $f_{1,2}(x)$, are defined by appropriate relations, e.g. as (16):

$$f_{1,1}(x) = e_j(x) \text{ i } f_{1,2}(x) = r_j(x) \quad (16)$$

Therefore, two tasks need to be solved:

a) maximize function (17):

$$f_{1,1}(x) = e_j(x),\ x \in X_1;\ j = 1,\dots,n \quad (17)$$

b) maximize function (18):

$$f_{1,2}(x) = r_j(x),\ x \in X_1;\ j = 1,\dots,n \quad (18)$$

Then determine the sets of X_1^1 i X_1^2 (19), (20):

$$X_1^1 = \{x^* \in X_1 : e_j(x^*) = \max_{x \in X_1} e_j(x)\} \quad (19)$$

$$X_1^2 = \{x^* \in X_1 : r_j(x^*) = \max_{x \in X_1} r_j(x)\} \quad (20)$$

and the set of dominant solutions as the product of the sets of X_1^1 i X_1^2 (21):

$$X_D^{\Phi 1} = X_1^1 \cap X_1^2 \quad (21)$$

If the set $X_D^{\Phi 1}$ is empty, the set of non-dominated solutions $X_N^{\Phi 1}$ and the set of compromise solutions $X_K^{\Phi 1}$ are determined.

According to the remarks made above, the maximum value of the function (19) and the maximum value of the function (20) determine the coordinates of the ideal point $c^* = (c_1^*, c_2^*)$ (22):

$$c_1^* = \max_{x \in X_1} e_j(x); \qquad c_2^* = \max_{x \in X_1} r_j(x) \quad (22)$$

From the adopted form of the criterion function $F_1 = \{f_{1,1}, f_{1,2}\}$ it follows that for c* the maximum value of e_j is demanded and the maximum value of r_j is demanded.

In further considerations, the normalized index of the quality of the solution of the task (5,6) will be used, which is proposed to be (23):

$$F_1^*(x) = \{f_{1,1}^*(x), f_{1,2}^*(x)\} \quad (23)$$

Where (24):

$$f_{1,1}^*(x) = \frac{f_{1,1}(x)}{c_1^{\max}},\quad f_{1,2}^*(x) = \frac{f_{1,2}(x)}{c_2^{\max}} \quad (24)$$

whereby (25):

$$c_1^{\max} = \max_{x \in X_1} f_{1,1}(x),\ c_2^{\max} = \max_{x \in X_1} f_{1,2}(x) \quad (25)$$

The advantage of this method of normalization is that the ratio is preserved after normalization. The highest value of the ratio is 1, and the lowest is greater than or equal to 0. The normalized ideal point then has coordinates (26):

$$c^{**} = (c_1^{**}, c_2^{**}) \quad (26)$$

Due to the form of the set of admissible solutions X_1 (discreteness) for determining the set of its non-dominated solutions $X_N^{\Phi 1}$ and compromise solutions $X_K^{\Phi 1}$, a method is proposed to determine the approximate result (and therefore the solution) of the compromise for the norm $|\bullet|$, which is a measure of the distance of the results c* ∈ C* from the ideal point c** [29].

Let c** denote the ideal point determined by relation (29) and C* the known set of normalized results (27):

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$$C^* = \{c^{*i}\},\ i = 1,\ldots,n \tag{27}$$

where $c^{*i} = (c_1^{*i}, c_2^{*i})$, whereby (28):

$$c_1^{*i} = \frac{c_1^i}{c_1^{\max}},\ c_2^{*i} = \frac{c_2^i}{c_2^{\max}} \tag{28}$$

In order to determine the compromise results, it is proposed to calculate the value of the $|\bullet|$ standard with the parameter p = 2 (29):

$$r_i = |c^{**} - c^{*i}|^2 = \sqrt{(c_1^{**} - c_1^{*i})^2 + (c_2^{**} - c_2^{*i})^2} \tag{29}$$

and selecting such a result c^o (30), which would minimize the calculated values of r_i norms. e.g. $x_1^o = x_{1,3}$

$$x_1^o = c^o = \min r_i \tag{30}$$

An interpretation of the above method is shown in Figure 2.

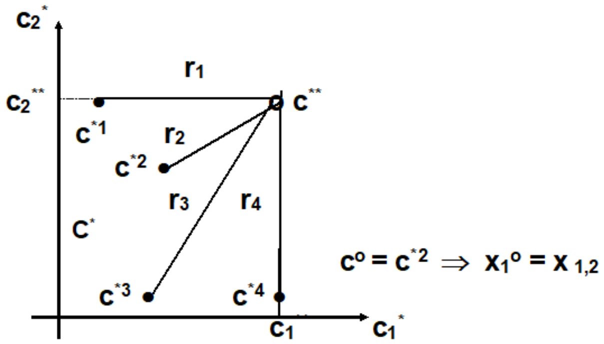
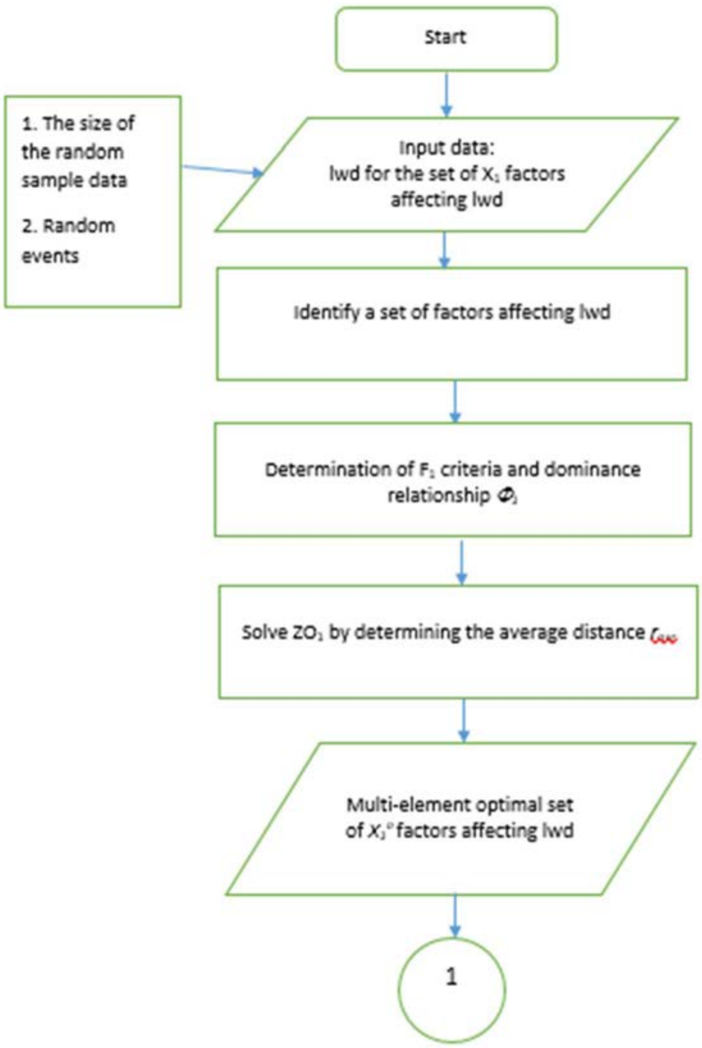


Figure 2 Graphical interpretation of the solution to the optimization task [28]

Based on the aforementioned insights, the following section outlines an algorithm that supports the proposed methodology for optimizing the traffic accident forecasting process (Figure 3).



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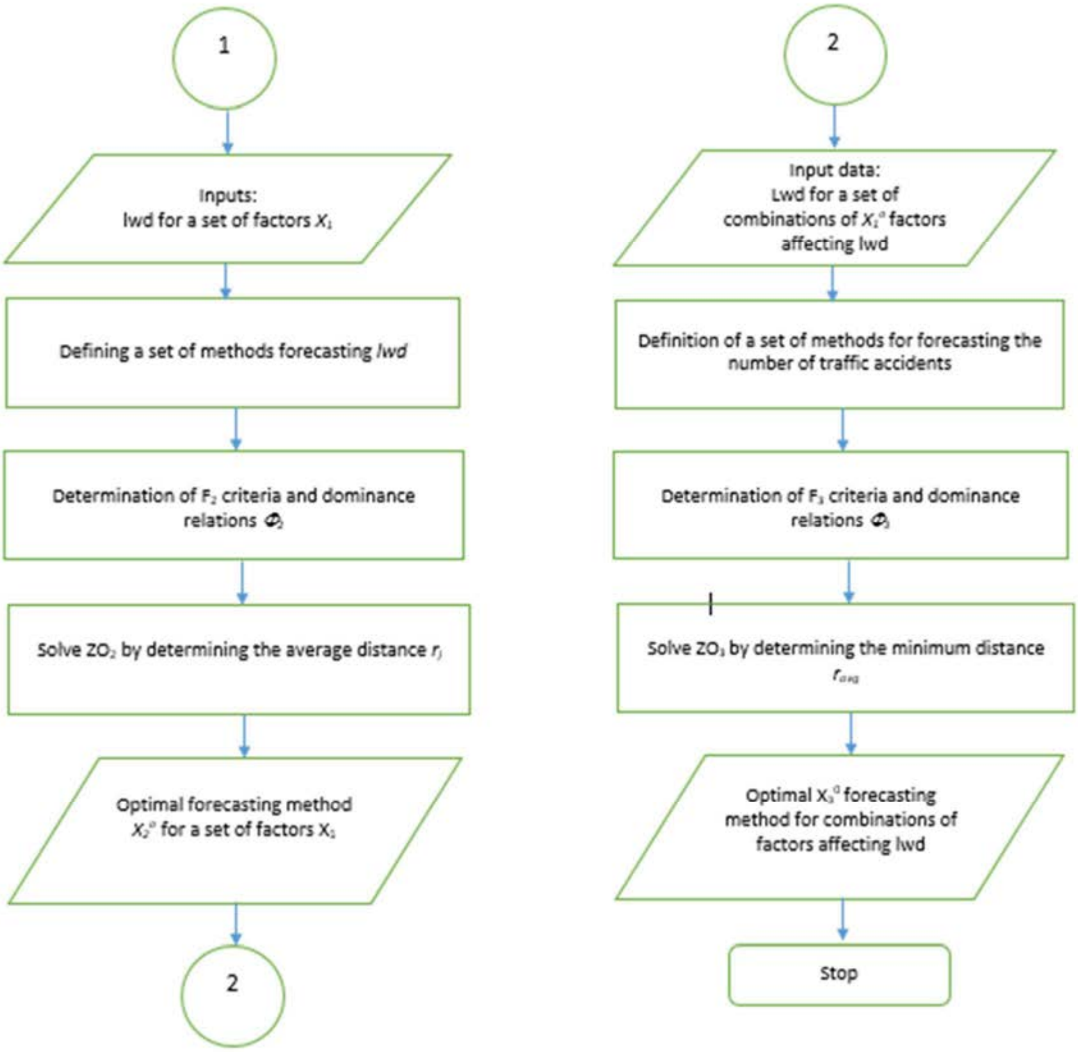

Figure 3 Schematic diagram of the methodology for optimizing the process of forecasting the number of road accidents

3 Conclusion

This study presents a methodological framework for optimizing the forecasting of road traffic accidents using a multi-criteria decision-making approach. The complexity of the problem, stemming from the multifactorial nature of road accidents and the limited quality of available data, necessitates a solution that can incorporate both quantitative and qualitative criteria. The proposed model formulates the forecasting process as a multi-objective optimization task, introducing sets of admissible solutions, partial objective functions, and dominance relations.

The developed algorithm enables the identification of dominant, non-dominated, and compromise solutions through normalization and distance-based evaluation, ensuring the adaptability of the method to varying data structures and decision-making preferences. The flexibility of the approach allows it to be applied in different contexts and with diverse sets of forecasting indicators.

The main advantage of the proposed methodology lies in its universality and scalability. It can be adapted to various forecasting challenges where both numerical and categorical indicators are relevant. Furthermore, the presented optimization framework provides a structured basis for supporting data-driven decisions in traffic safety management.

Future research may extend this approach to real-time data environments, include dynamic factors (e.g., weather or traffic flow), and integrate machine learning techniques to enhance predictive accuracy and operational efficiency.

References

[1] WHO, Global status report on road safety 2020, Geneva: World Health Organization, Annual report, [Online], Available: https://www.who.int/violence_injury_prevention/road_safety_status/report/en/ [18 May 2025], 2020.

[2] Eurostat, [Online], Available: https://ec.europa.eu/eurostat [18 May 2025], 2024.

[3] Police Statistics, [Online], Available: https://statystyka.policja.pl/st/ruch-drogowy/76562,Wypadki-drogowe-raporty-roczne.html [10 May 2025], 2024.

[4] ZHAI, X., HUANG, H., SZE, N.N., SONG, Z., HON, K.K.: Diagnostic analysis of the effects of weather condition on pedestrian crash severity, *Accident Analysis & Prevention*, Vol. 122, pp. 318-324, 2019. https://doi.org/10.1016/j.aap.2018.10.017

[5] HOLLAND, C., HILL, R.: The effect of age, gender and driver status on pedestrians' intentions to cross the road in risky situations, *Accident Analysis & Prevention*, Vol. 39, No. 2, pp. 224-237, 2007. https://doi.org/10.1016/j.aap.2006.07.003

[6] FAVARÒ, F.M., NADER, N., EURICH, S.O., TRIPP, M., VARADARAJU, N.: Examining accident reports involving autonomous vehicles in California, *PLOS ONE*, Vol. 12, No. 9, pp. 1-20, 2017. https://doi.org/10.1371/journal.pone.0184952

[7] AMINI, R.E., KATRAKAZAS, C., ANTONIOU, C.: Negotiation and decision-making for a pedestrian roadway crossing: A literature review, *Sustainability*, Vol. 11, No. 23, pp. 1-24, 2019. https://doi.org/10.3390/su11236713

[8] HAFEEZ, F., SHEIKH, U.U., AL-SHAMMARI, S., HAMID, M., KHAKWANI, A.B.K., ARFEEN, Z.A.: Comparative analysis of influencing factors on pedestrian road accidents, *Bulletin of Electrical Engineering and Informatics*, Vol. 12, No. 1, pp. 257-267, 2023. https://doi.org/10.11591/eei.v12i1.4312

[9] MESQUITELA, J., ELVAS, L.B., FERREIRA, J.C., NUNES, L.: Data Analytics Process over Road Accidents Data—A Case Study of Lisbon City, *ISPRS International Journal of Geo-Information*, Vol. 11, No. 2, 143, pp. 1-18, 2022. https://doi.org/10.3390/ijgi11020143

[10] BECKER, N., RUST, H.W., ULBRICH, U.: Predictive modeling of hourly probabilities for weather-related road accidents, *Natural Hazards and Earth System Sciences*, Vol. 20, No. 10, pp. 2857-2871, 2020. https://doi.org/10.5194/nhess-2020-10

[11] MILLS, B., ANDREY, J., DOBERSTEIN, B., DOHERTY, S., YESSIS, J.: Changing patterns of motor vehicle collision risk during winter storms: A new look at a pervasive problem, *Accident Analysis Prevention*, Vol. 127, pp. 186-197, 2019. https://doi.org/10.1016/j.aap.2019.02.027

[12] KARLAFTIS, M., YANNIS, G.: *Weather effects on daily traffic accidents and fatalities: A time series count data approach*, Transportation Research Board 89th Annual Meeting Location: Washington DC, United States 2010, 2010.

[13] BERGEL-HAYAT, R., DEPIRE, A.: *Climate, road traffic and road risk – An aggregate approach*, 10th World Conference Transport Research, Istanbul, Turkey, 2004.

[14] HERMANS, E., WETS, G., VAN DEN BOSSCHE, F.: Frequency and severity of belgian road traffic accidents studied by state-space methods, *Journal Transportation and Statistics*, Vol. 9, No. 1, pp. 63-76, 2006.

[15] BIJLEVELD, F., CHURCHILL, T.: The Influence of Weather Conditions on Road Safety: An Assessment of the Effect of Precipitation and Temperature, [Online], Available: https://www.swov.nl/sites/default/files/publicaties/rapport/r2009-09.pdf [24 Aug 2024], 2024.

[16] BUCSUHÁZY, K., MATUCHOVÁ, E., ZUVALA, R., MORAVCOVÁ, P., KOSTÍKOVÁ, M., MIKULEC, R.: Human factors contributing to the road traffic accident occurrence, *Transportation Research Procedia*, Vol. 45, pp. 555-561, 2020. https://doi.org/10.1016/j.trpro.2020.03.057

[17] KIM, D., YOON, S., KIM, B.: Comparison of spatial interpolation methods for producing road weather information in winter, *Journal of The Korean Data Analysis Society*, Vol. 23, No. 2, pp. 541-551, 2021. https://doi.org/10.37727/jkdas.2021.23.2.541

[18] KIM, D., JUNG, S., YOON, S.: Risk Prediction for Winter Road Accidents on Expressways, *Applied Sciences*, Vol. 11, No. 20, 9534, pp. 1-12, 2021. https://doi.org/10.3390/app11209534

[19] ONESIMU, J.A, KADAM, A., SAGAYAM, K.M, ELNGAR, A.A.: Internet of things based intelligent accident avoidance system for adverse weather and road conditions, *Journal of Reliable Intelligent Environments*, Vol. 7, pp. 299-313, 2021. https://doi.org/10.1007/s40860-021-00132-7

[20] TUBIS, A.: Risk Assessment in Road Transport – Strategic and Business Approach, *Journal of KONBiN*, Vol. 45, pp. 305-324, 2018. https://doi.org/10.2478/jok-2018-0016

[21] SafetyCube: Project co-funded by by Horizont 2020 Framework Program European Union, 2016, [Online], Available: https://www.safetycube-project.eu/ [10 Jul 2024], 2016.

[22] REURINGS, M., JANNSEN, T.: *Accident prediction models for urban and rural carriageways*, SWOV Institute for Road Safety Research, SWOV, Leidschendam, The Netherlands, 2007.

[23] European Commission: Road Infrastructure Safety Management Evaluation Tools, [Online], Available: https://trimis.ec.europa.eu/project/road-infrastructure-safety-management-evaluation-tools [10 Jul 2024], 2011.

[24] HAYAT, R., DEBBARH, M., ANTONIOU, C., YANNIS, G.: Explaining the road accident risk: Weather effects, *Accident Analysis & Prevention*, Vol. 60, No. November, pp. 456-465, 2013. https://doi.org/10.1016/j.aap.2013.03.006

[25] HERMANS, E., BRIJS, T., STIERS, T., OFFERMANS, C.: *The impact of weather conditions on road safety investigated on an hourly basis,*

Proceedings of the 85th Transportation Research Board (TRB) Annual Meeting, Washington, D.C., USA, 2006.

[26] BRODSKY, H., HAKKERT, A.S.: Risk of a road accident in rainy weather, *Accident Analysis & Prevention*, Vol. 20, No. 3, pp. 161-176, 1988. https://doi.org/10.1016/0001-4575(88)90001-2

[27] SABIR, M.: *Weather and Travel Behaviour*, Dissertation, Vrije Universiteit Amsterdam, Amsterdam, Netherlands, 2011.

[28] GORZELANCZYK P., TYLICKI H.: Methodology for optimizing factors affecting road accidents in Poland, *Forecasting*, Vol. 5, No. 1, pp. 336-350, 2023. https://doi.org/10.3390/forecast5010018

[29] BHANDARI, B., LEE, K.-T., LEE, G.-Y., CHO, Y.-M., AHN, S.-H.: Optimization of hybrid renewable Energy power systems: A review, *International Journal of Precision Engeering and manufacturing-Green Technology*, Vol. 2, No. 1, pp. 99-112, 2015. https://doi.org/10.1007/s40684-015-0013-z

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Application and potential of 4D printing in medicine

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Abstract: 4D printing represents a groundbreaking technology that extends the possibilities of 3D printing by adding a dynamic dimension—time. By using smart materials capable of changing their shape or properties in response to external stimuli such as temperature, humidity, or pH, new horizons are opening, especially in the field of medicine. This article presents the basic principles of 4D printing, explains the nature of functional materials and mechanisms that enable programmable behaviour, and focuses on specific applications in the medical context. The most promising areas include implants that can adapt to anatomical changes, targeted drug delivery systems, bioprinting of tissues and organs, and novel types of rehabilitation devices. The article also discusses the benefits of this technology, such as reduced invasiveness of medical procedures, improved functionality of medical devices, and enhanced treatment personalization. At the same time, it reflects on the challenges associated with 4D printing development—from material selection and technical or regulatory limitations to the need for interdisciplinary collaboration. The goal of this paper is to present the current state of knowledge in this field, identify its potential and limitations, and support further research and clinical validation of 4D technologies in medicine.

1 Introduction

In recent decades, 3D printing has undergone rapid development, significantly influencing various industrial sectors. Whether in aerospace, mechanical engineering, robotics, biomedicine, or healthcare, 3D printing has established a prominent position across all these fields. Linked with CAD and CAM platforms, this technology facilitates the development of sophisticated geometries and components that are beyond the practical limits of conventional fabrication techniques. By gradually depositing material layer by layer, highly detailed and customized components can be fabricated.

In medicine and biomedicine, 3D printing has brought about groundbreaking innovations, particularly in the areas of implants, targeted drug delivery systems, tissue engineering, and regenerative medicine.

Technological progress has naturally paved the way for further innovation. As a result, 3D printing has become the foundation for a new concept—4D printing. This approach involves the production of structures capable of changing their shape or properties in response to external stimuli such as variations in pH, temperature, pressure, or humidity. While building upon the principles of 3D printing, 4D printing expands additive manufacturing into a dynamic dimension.

By incorporating time as the fourth dimension, 4D printing enables materials and structures to adapt their geometry, mechanical properties, or functions dynamically [1]. This transformation is made possible through the use of smart materials specifically designed and "programmed" to respond to environmental conditions.

2 Principle of 4D printing

4D printing extends traditional 3D printing by introducing the ability to program time-dependent transformations of objects in response to external stimuli. From a technological perspective, 4D printing requires precise control over geometry, fiber orientation, and internal stress distribution to achieve the desired shape or function upon activation. For instance, a polymer implant with shape memory properties can unfold into its target configuration at body temperature without requiring mechanical expansion [2].

2.1 Key factors and principles affecting 4D printing

The successful implementation of 4D printing relies on five key components:

1. Additive Manufacturing (AM) process – enables the direct production of structures from digital models without intermediate tooling. Technologies used include SLA (stereolithography), SLS (selective laser sintering), FDM (fused deposition modeling), 3DP (three-dimensional printing), SLM (selective laser melting), DIW (direct ink writing), and EBM (electron beam melting).
2. Material selection – materials must be compatible with the AM process and capable of responding to external stimuli. These so-called smart or programmable materials determine the type and nature of the transformation.
3. External stimuli – can be physical (temperature, humidity, light, magnetic fields), chemical (pH, redox agents), or biological (enzymes, glucose), and initiate structural changes.
4. Interaction mechanism between the material and the stimulus – ensures proper stimulus transmission and sequence of transformation.
5. System behaviour modelling – allows for prediction of timing and transformation dynamics, often using numerical simulations [1].

The integration of these components enables the creation of 4D-printed structures that actively change over time in response to specific stimuli.

F. Momeni and J. Ni defined three fundamental laws that describe shape transformation mechanisms in multi-material 4D-printed structures [3]:

First law: Shape transformation (e.g., bending, twisting, coiling) occurs due to differential strain between active and passive materials.

Second law: Four fundamental phenomena account for the observed strain: mass diffusion, thermal expansion, molecular transformations, and organic growth. These are activated by external factors including temperature, light, pH variation, or mechanical loading.

Third law: Transformations exhibit time-dependent behavior governed by two time constants, which vary with the material and stimulus type. A biexponential mathematical model has been proposed to simulate these transformations during the design of 4D structures [3].

2.2 Overview of 3D printing techniques suitable for 4D printing

Various 3D printing technologies can be employed for 4D printing, differing in their working principles, material compatibility, and resolution. The following overview presents the most relevant techniques suitable for 4D applications, along with their characteristics and example uses.

Fused Deposition Modeling - FDM

FDM is a widely used technique in which thermoplastic material is extruded through a nozzle and deposited layer by layer along the X, Y, and Z axes to form a 3D (or 4D) object. It is popular due to its low cost, simplicity, and flexibility for developing new materials.

Tian et al. [4] developed an FDM approach for carbon fiber-reinforced composites (CFRTC), enabling the fabrication of mechanically robust structures. Bodaghi et al. [83] demonstrated the use of FDM for shape memory materials (SMEs). Current research focuses on improving FDM's efficiency with novel smart materials.

Stereolithography - SLA

SLA uses photopolymers that solidify upon exposure to light (typically UV or visible). The light initiates a chemical reaction leading to resin cross-linking and the formation of solid structures.

This method allows for the precise fabrication of complex geometries, and research is ongoing to expand the range of compatible materials.

Notably, the first demonstration of 4D printing was achieved using SLS technology with UV light on a Stratasys Connex printer [5].

Selective Laser Sintering - SLS

SLS employs a laser to selectively fuse powdered material in successive layers. This technique accommodates a broad spectrum of substances, such as waxes, metals, ceramics, and polymers including PU, PCL, PEEK, and polyamide [6-8].

Selective Laser Melting - SLM

SLM is similar to SLS, but the powder is completely melted, resulting in a homogeneous structure with no post-sintering required. The laser beam's speed and intensity can be tailored to the material, making SLM particularly suitable for metal printing [9].

Directed Energy Deposition - DED

DED is designed for metal part fabrication. Material in the form of powder or wire is melted at the point of deposition using a thermal source, typically a laser or electron beam. It is also applicable for printing shape memory structures [10-12].

InkJet printing

Inkjet printing uses tiny droplets of material deposited layer by layer. It is employed in the fabrication of low-cost electronics and wearable devices (e.g., sensors, displays) on polymer substrates such as PET and PEN [13,14], as well as in bioprinting of cells and tissues [15].

Direct Ink Writing - DIW

DIW is similar to FDM but supports a wider range of materials, including thermoplastics, hydrogels, and sol-gel inks. It is particularly suitable for soft and bioactive systems.

Projection Micro-Stereolithography - PμSL

PμSL and DIW are advanced techniques used primarily in biomedical 4D printing applications, offering high precision and compatibility with sensitive materials at micrometer resolution.

2.3 Materials

From a materials perspective, 4D printing utilizes stimuli-responsive polymers (e.g., SMPs), hydrogels, or shape memory alloys (e.g., nitinol), whereas 3D printing primarily relies on thermoplastics, photopolymers, metals, or ceramics. Material selection is crucial to ensure the desired functionality of the object during activation [16].

The materials used in 4D printing are known as smart materials due to their ability to dynamically change their properties over time in response to external stimuli [17]. These materials exhibit complex functions such as self-assembly, self-healing, shape memory, or self-regulation [18]. In addition to morphological changes, 4D printing also enables changes in optical properties, such as colour, when exposed to UV or visible light.

2.3.1 Classification of smart materials used in 4D printing

The materials used in 4D printing are referred to as smart because they are capable of dynamically altering their properties in response to external stimuli. These materials are also called stimuli-responsive and can react to triggers such as temperature, light, electric or magnetic fields, humidity, pH, chemical substances, or biological factors. The result of such a reaction may include changes in shape, volume, colour, stiffness, or other mechanical properties.

The following figure (Figure 1) schematically illustrates the classification of smart materials according to the type of external stimulus and the material's response. This overview provides a better understanding of what materials may be suitable for 4D printing depending on the desired functionality.

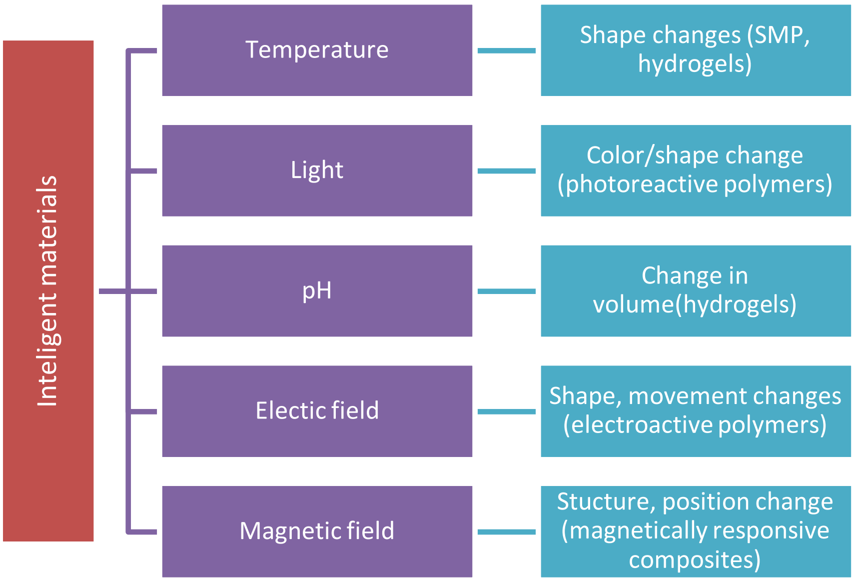

Figure 1 Intelligent materials and their stimuli reactions

From the perspective of responsiveness, smart materials used in 4D printing are most commonly divided into two main categories:

1. Shape-memory materials - SMM

These materials have the ability to "remember" their original shape and return to it after being exposed to a specific stimulus (e.g., heat or light). They enable the creation of temporarily deformed structures that later reconstruct into the desired form. They are used, for example, in the development of biodegradable scaffolds or implants that adapt to the target anatomical site after implantation.

2. Shape-changing materials

These materials change their shape or physical properties during the presence of a stimulus, but do not return to their original state once the stimulus is removed. Typical representatives include hydrogels, electroactive polymers, or magnetically responsive composites. They are primarily applied in controlled drug delivery systems, soft robotics, or the design of adaptive tissue structures.

Table below (Table 1) provides a classification of smart materials commonly used in 4D printing, based on the type of external stimulus they respond to, their response behaviour, and typical applications. The materials are divided into categories such as shape-memory, shape-changing, hybrid, and adaptive materials, each exhibiting unique functionalities that enable dynamic changes in shape, mechanical properties, or biological activity.

Shape-memory materials (e.g., SMPs and nitinol) can recover their original shape upon exposure to specific stimuli like heat or light, making them suitable for medical implants, scaffolds, and minimally invasive surgical tools.

Shape-changing materials respond by altering shape or properties temporarily during stimulation but do not revert back automatically, which is useful in drug delivery systems, soft robotics, and actuators.

Hybrid materials combine different responsive behaviors, such as changes in stiffness or volume, offering advanced applications like photothermal therapy or environmental control.

Adaptive materials such as bioinks respond to biochemical signals to facilitate tissue formation, playing a vital role in regenerative medicine and bioprinting.

This classification highlights the versatility of smart materials and their potential to revolutionize personalized medicine, biomedical devices, and responsive structures through 4D printing technology.

Table 1 Classification of smart materials used in 4D printing based on their stimulus type, response behavior, category, and typical applications

Material Type	Stimulus	Response Type	Category	Typical Application
SMP (Shape-memory polymer)	Heat, light	Return to original shape	Shape-memory	Scaffolds, stents, surgical implants
Nitinol (alloy)	Heat	Shape recovery	Shape-memory (metal)	Orthopedics, minimally invasive tools
Hydrogel	pH, temperature	Swelling, shrinking	Shape-changing	Tissue engineering, drug delivery
Electroactive polymer	Electric field	Contraction, bending	Shape-changing	Actuators, biosensors
Magnetic composite	Magnetic field	Bending, deformation	Shape-changing	Soft robotic structures, targeted therapy
Thermoresponsive polymer	Temperature	Change in stiffness, volume	Hybrid	Photothermal therapy, environmental regulation
Bioink	Biochemical cues, growth factors	Formation of functional tissue	Adaptive	Regenerative medicine, 3D bioprinting

The development of smart materials that react to external stimuli constitutes a crucial element of 4D printing within biomedical engineering. Such materials allow for the fabrication of dynamic constructs capable of altering their geometry or properties in response to environmental conditions. Their application in 4D printing paves the way for innovative healthcare approaches, particularly in the field of personalized and adaptive therapies.

2.3.2 Typology of used materials

Materials used in 4D printing can be divided into four basic groups:

- **Biological materials** (derived from plants or traditional medicines) – offering natural biocompatibility and biodegradability.
- **Bio-based materials** (e.g., natural polymers, hydrogels) – mimicking the extracellular matrix and supporting tissue regeneration.
- **Synthetic materials** (e.g., thermoplastics, shape-memory polymers – SMP) – providing high mechanical strength and precise property control.
- **Hybrid materials** – combining advantages of natural and synthetic components, such as bioactivity and mechanical strength.

The choice of material depends on the specific application requirements, such as biocompatibility, degradation profile, mechanical demands, or target tissue. Research continues to develop new or optimized materials that expand the possibilities of 4D printing in biomedicine.

Shape-memory Polymers - SMP

Shape-memory polymers represent one of the most widely applied smart materials in 4D printing. They are capable of reverting from a deformed configuration back to their original form when exposed to specific stimuli, such as heat or light [19]. This feature allows for the fabrication of constructs that can adapt automatically to patient anatomy after implantation. For instance, an SMP-based scaffold may reconfigure at body temperature to accurately fit the tracheal structure, thereby improving surgical outcomes [20].

Hydrogels

Hydrogels are another important type of smart materials used in 4D printing. They are polymer networks that respond to changes in temperature or pH by swelling or shrinking [21,22]. They are primarily used in tissue engineering and controlled drug delivery systems. For instance, a hydrogel system can release drugs in a controlled manner at a specific temperature, improving treatment accuracy [23].

Thermoresponsive polymers

These polymers change their physical properties (shape, stiffness, volume) depending on temperature. Wang et al. [24] developed a system based on dual thermoresponsive polymers with different phase transition temperatures, allowing precise control of thermal response. Using 4D printing, it is possible to create structures with tunable properties that undergo changes when exposed to thermal stimuli such as laser irradiation. This technology shows great promise for enhancing the safety and efficacy of photothermal therapy.

Electroactive and magnetically responsive materials

Materials responsive to electric or magnetic fields, such as electroactive polymers and magnetically responsive composites, are promising for the development of advanced medical devices. They can change their shape or mechanical properties and are used in soft robotic prosthetics, dynamic implants, or targeted drug delivery systems [21,25]. For example, Zhao et al. [25] designed a tracheal scaffold that responds to a magnetic field by combining magnetic particles with shape-memory composites, enabling real-time controllable adaptability.

Bioinks

Bioinks – biocompatible materials often containing living cells – play a crucial role in biomedical engineering. Their use in 4D printing enables the creation of structures that develop over time into functional tissues. For example, a skeletal muscle model produced using electrically aligned bioink demonstrated potential in regenerative medicine [26].

2.3.3 Rheological properties of polymers

In polymer-based additive manufacturing, rheological properties significantly affect the quality and accuracy of 4D printing [27]. Parameters such as viscosity, shear-thinning behaviour, and thixotropy influence material flow, extrusion capability, and shape fidelity. Optimizing these properties is essential for successfully producing complex and delicate biomedical constructs.

3 Applications of 4D printing in medicine

In the context of medicine, 4D printing brings groundbreaking possibilities: implants that activate within the body, drug carriers with targeted release, or scaffolds that dynamically change during tissue healing. These features enhance therapeutic efficacy, shorten treatment duration, and minimize the number of surgical interventions [28].

3.1 Biomedical implants and prostheses

4D printing technology introduces significant innovations in implantology and prosthetics through structures capable of actively responding to conditions inside the patient's body. Unlike traditional implants, which are rigid and static, 4D printed implants can dynamically adapt. Their shape, stiffness, or mechanical properties change in response to stimuli such as temperature, pH, or pressure. This improves their ability to conform to the patient's anatomy and the dynamic environment within the organism [29,30].

An example of such an adaptive solution is the use of biodegradable shape-memory scaffolds for bone defect repair. This approach allows precise individual customization while ensuring gradual biological integration at the defect site, consistent with core principles of 4D printing like shape memory, biodegradation, and osteoinduction.

3.1.1 Self-forming and adaptive implants

One of the promising applications of 4D printing in implantology involves self-forming and adaptive implants that adjust to the target environment within the human body after implantation. Their development relies on smart materials such as shape-memory polymers (SMPs) and stimulus-responsive hydrogels, which alter their shape or mechanical properties in response to specific physiological triggers like temperature, humidity, or pH [31].

A typical example includes 4D printed stents designed to expand at body temperature (37°C) once placed inside a vessel, restoring blood flow in a narrowed section [28]. Some stents are made from biodegradable polymers and gradually degrade after fulfilling their function, eliminating the need for surgical removal. Others use shape-memory metal alloys like nitinol, which, although non-degradable, provide superelasticity for safe and reliable deployment (Figure 2).

In orthopedics, implants capable of altering stiffness based on mechanical load are being explored, allowing better adaptation to bone biomechanics. Such implants can significantly improve healing, reduce stress shielding, and promote integration with living tissue [32].

Clinically, these solutions hold potential to reduce surgical invasiveness, improve patient comfort, and enhance long-term implant functionality. Despite these benefits, challenges remain regarding precise control of biodegradation timing and long-term biocompatibility of materials such as nitinol, which may cause microinflammatory reactions if not adequately managed.

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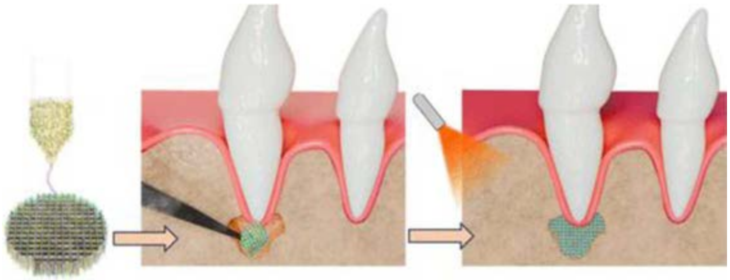

Figure 2 Self-expanding stent made of shape memory polymer (SMP) [33]

3.1.2 Regenerative medicine

Beyond orthopedic and vascular implants, 4D printing finds application in regenerative medicine by creating supportive scaffolds intended for tissue repair. Stimuli-responsive hydrogels play a crucial role; these materials can modify their architecture, porosity, or mechanical properties after implantation according to the healing process [34].

These so-called programmable scaffolds mimic the natural extracellular matrix and actively adapt throughout regeneration. During the initial inflammatory phase, they remain soft and permeable to nutrients, while later stiffening to stabilize newly formed tissue [35].

They are utilized in treatments of skin defects, burns, cartilage damage, and peripheral nerve injuries [36]. Some hydrogel structures are enriched with growth factors or patient-derived cells to enhance biological effectiveness. Multi-layered scaffolds combining different cell types or bioactive substances depending on injury depth are also under experimental investigation [1].

The primary advantage of 4D printing in regenerative medicine lies in scaffolds with temporally dynamic behavior—the structure evolves alongside regenerating tissue, providing optimal support at each healing phase. This functional adaptability sets them apart from passive 3D scaffolds, which remain static post-implantation. Given the rapid advances in biomaterials and bioprinting technologies, intelligent scaffolds are expected to play a key role in personalized regenerative medicine soon. While some hydrogel scaffolds for skin lesions have passed early clinical trials, most multi-layered and bioactivated constructs remain in preclinical stages.

3.2 Tissue engineering and bioprinting

4D printing technology significantly enhances the potential of tissue engineering by enabling the creation of biological structures with dynamic behavior. Using smart biomaterials, it is possible to fabricate scaffolds that actively respond to stimuli such as temperature, pH, or mechanical stress after implantation [1,35].

A key component of these dynamic systems is shear-thinning hydrogels—materials whose viscosity decreases under mechanical load, allowing easy extrusion during bioprinting. Once printed, they stabilize into well-defined structures. When combined with cells or bioactive molecules, they serve as bioinks that support cell growth and differentiation [37].

4D bioprinted scaffolds can adapt over time by adjusting porosity, elasticity, or releasing growth factors based on the regeneration stage. They are being tested in the treatment of cartilage, skin, peripheral nerve, and muscle tissue injuries [38].

Promising outcomes have also been achieved with bioprinted heart valves and artificial vessels that adjust elasticity or diameter in response to blood flow and pressure, improving long-term implant performance and reducing failure risks [39].

By combining biocompatibility, adaptability, and spatial precision, 4D bioprinting is a key tool in developing personalized, functional, and time-responsive tissue replacements.

3.2.1 4D printing of biological structures and organs

4D bioprinting represents a major advancement in producing functional biological structures that change their properties in response to physiological stimuli. These constructs are typically made from hydrogels combined with living cells and can respond to changes in temperature, pH, or mechanical stress (

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Figure 3).

The goal goes beyond anatomical replication—4D bioprinted scaffolds are designed to mimic natural processes like remodeling, angiogenesis, and cell differentiation [39]. They support tissue regeneration and maintain mechanical stability during healing. Current research focuses on:

- heart valves that adjust elasticity based on blood flow,
- artificial vessels adapting their diameter to blood pressure,
- multilayered tissues (e.g., liver or pancreas) with diverse cell types and vascularization [1].

Although still in experimental and preclinical stages, results show strong clinical potential. Personalization based on patient-specific data reduces the risk of rejection. In the future, 4D bioprinting is expected to enable functional tissue and partial organ implants that dynamically adapt to the body's needs. Advances in vascularization and tissue integration point to realistic clinical applications in the coming decades.

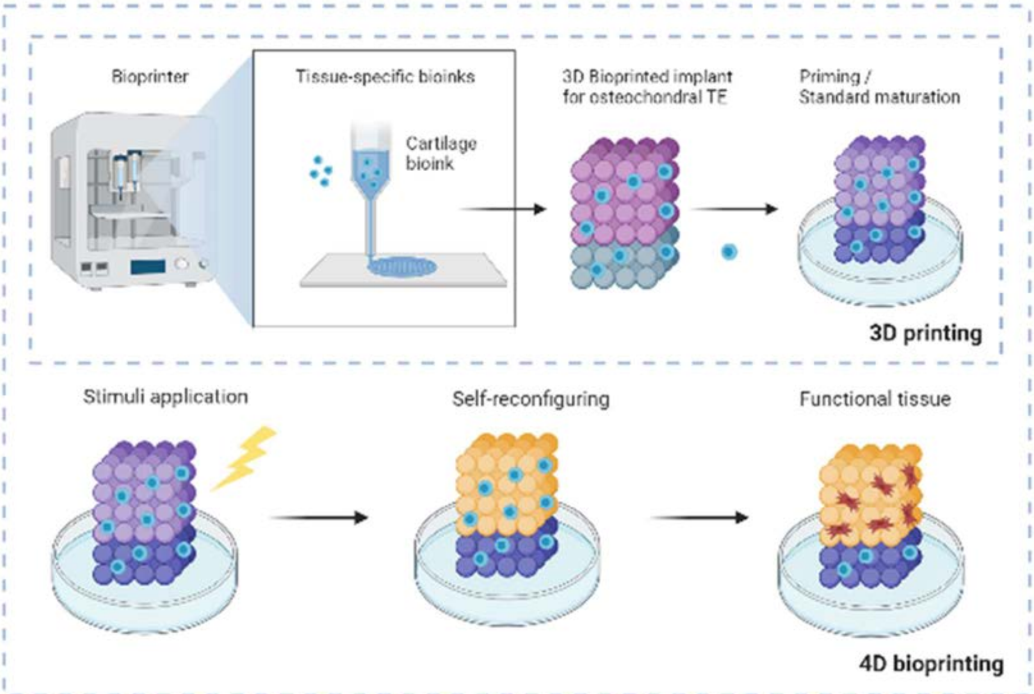

Figure 3 4D bioprinting process for osteochondral tissue engineering

3.2.2 Peripheral nerve regeneration

Peripheral nerve regeneration poses a major challenge, especially in large defects where traditional autografts or static conduits are insufficient. 4D printing enables the development of intelligent nerve guidance conduits (NGCs) that actively adapt to surrounding tissue after implantation—changing shape at body temperature or responding to humidity and pH, thereby improving contact with the nerve stump without manual adjustment [34,36].

These structures can incorporate conductive materials (e.g., MXenes, carbon nanotubes) to enable electrical stimulation of axons, enhancing regeneration [36]. A 2021 study demonstrated that a biodegradable, self-expanding 4D-printed conduit with enhanced conductivity improved both axonal regeneration and motor function in a preclinical model (Figure 4). While still in the experimental phase, this approach shows great promise for personalized, minimally invasive, and functionally active treatments for peripheral nerve injuries [40].

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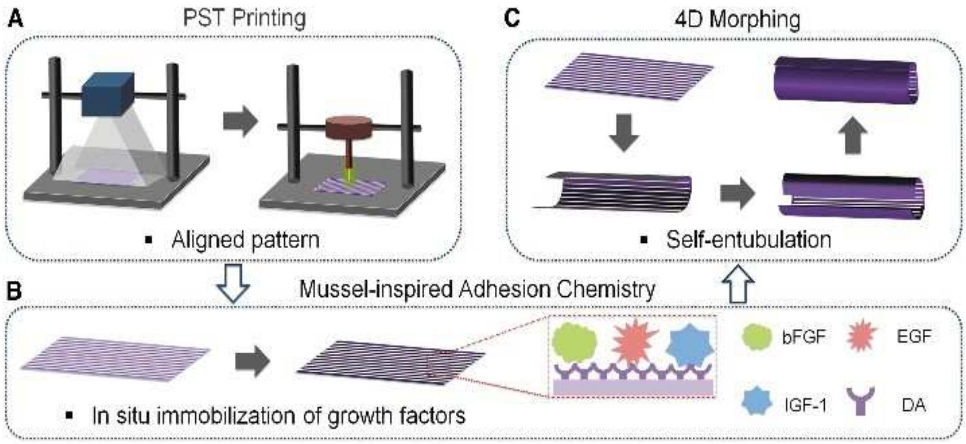

Figure 4 4D-printed nerve guidance conduit that self-closes after implantation, adapts to surrounding tissue, and supports peripheral nerve regeneration

3.3 Personalized medicine and pharmacy

Personalized medicine focuses on tailoring diagnostics and therapy to an individual's genetic, biological, and lifestyle characteristics. In this context, 4D printing is a crucial tool for designing smart drug carriers and medical devices that respond to specific in vivo conditions. Using 4D printing, drug delivery systems can be designed to release medications at precise times and locations, improving efficacy and reducing side effects. Smart implants or capsules can change shape or porosity based on local stimuli such as pH or enzymes, allowing targeted and controlled release [41].

3.3.1 Intelligent drug delivery systems

4D printing offers innovative opportunities in pharmaceutical applications by enabling smart drug delivery. Unlike traditional dosage forms that release drugs passively, 4D-printed systems can respond to specific physiological stimuli and release active substances in a targeted and adaptive manner.

Adaptive Drug Release Systems

A common example is pH-sensitive polymer capsules that remain intact in the acidic environment of the stomach but dissolve in the more alkaline intestines—ideal for treating intestinal inflammation or infections. Similarly, temperature-responsive hydrogels can change their volume or porosity depending on body temperature, regulating drug diffusion [38].

Multilayer and Multi-Component Tablets

4D printing allows the design of tablets with multiple layers or components, each releasing a different drug or excipient at a specific time or location. This is especially useful for patients with chronic conditions like diabetes, hypertension, or asthma who require complex dosing regimens [1].

Stimuli-Responsive Drug Carriers

The most advanced systems are stimuli-responsive carriers that release drugs in response to triggers like pH, enzymes, light, magnetic fields, or ultrasound. These are being developed mainly for targeted cancer therapy, aiming to maximize drug concentration at the tumor site while sparing healthy tissue [42].

Designing such systems requires precise control over material properties and drug distribution. 4D printing enables integration of active and passive components into a single structure, ensuring accurate dosage, targeting, and release timing.

Currently, these systems are under investigation in oncology, targeted antibiotic delivery, immunotherapy, and chronic inflammatory diseases.

3.3.2 4D printing of customized medical devices

4D printing technology enables the design of medical devices that actively respond to stimuli and adapt to the individual needs of patients. Implants made from shape-memory materials, such as nickel-titanium (nitinol), change their shape upon reaching physiological temperature, allowing precise deployment at the target site without the need for manual adjustment [32]. This principle is commonly used in endovascular procedures, such as the implantation of stents or vascular reinforcements.

In pediatric surgery, implants that respond to the growth of the organism are being experimentally tested, enabling adaptation without repeated surgical replacement during the child's development [30,39].

A significant area of 4D printing research involves active medical devices whose functionality changes in response to specific physiological stimuli. Examples include stents with programmable diameters that expand at body temperature or respond to changes in mechanical load at the target site, such as fluctuations in blood pressure (Figure 5) [30,38].

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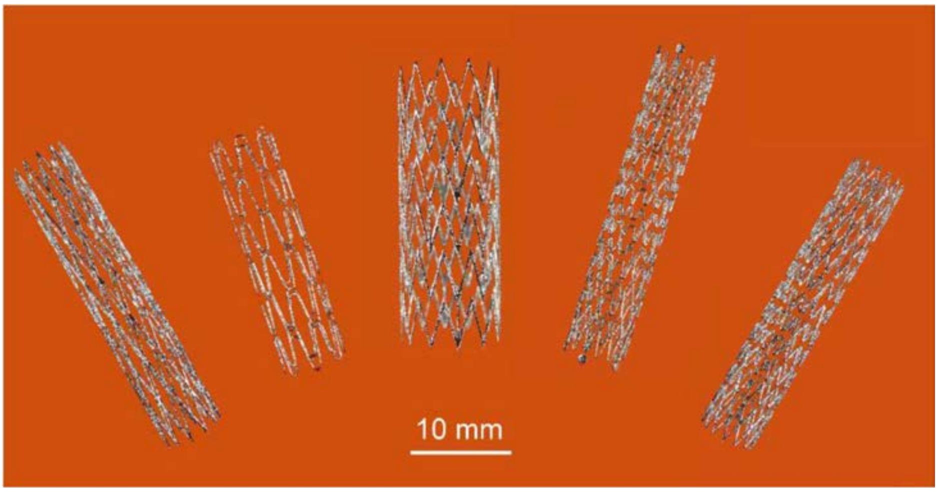

Figure 5 Self-expanding nitinol stents produced by 3D printing using selective laser melting (SLM) at the Lab22 laboratory (CSIRO, Melbourne)

Implants with modified surfaces can detect inflammation and release bioactive agents, such as antibacterial and immunomodulatory compounds. These systems enable targeted local drug delivery, enhancing efficacy while reducing side effects and the need for systemic therapy. Thus, 4D printing supports not only personalized design but also the development of smart devices with improved therapeutic performance [43].

3.3.3 Personalized pharmacotherapy and dosing

Modern pharmacotherapy faces the challenge of achieving precise dosing that considers individual physiological and genetic characteristics. Conventional drug regimens often overlook variability in metabolism, weight, age, genetic polymorphisms, or comorbidities.

4D printing enables the creation of personalized drug delivery systems that respond to specific physiological conditions and release active substances based on predefined parameters. Such systems can:

- release drugs at programmed time intervals,
- respond to stimuli (e.g., pH, enzymes, temperature),
- adjust dosing in real time based on patient status.

These features are especially valuable in chronic diseases (e.g., diabetes, rheumatoid arthritis, neurological disorders), where therapy must align with daily rhythms or symptom cycles.

Polymers with programmed degradation and stimuli-responsiveness, combined with genetic or biomarker data, allow for fully personalized dosing strategies. In the future, integration with wearable diagnostic sensors could enable real-time adaptation of drug delivery, leading to smart, adaptive, and highly individualized pharmacotherapy[34].

3.4 *Adaptive sutures and bandages*

Among the promising surgical applications of 4D printing is the development of adaptive sutures and bandages. These systems respond to changes in the wound or surrounding skin, enhancing treatment effectiveness and patient comfort. Most often, they utilize shape memory polymers (SMPs), which can alter their shape or tension in response to body temperature, moisture, or pH levels [4].

3.4.1 Self-tightening sutures

Traditional sutures require manual closure and are often removed later by a physician. With SMPs, it is possible to design sutures that automatically contract at a specific temperature—typically 37°C. They ensure even wound closure without the need for manual tension adjustment and adapt to changes in wound shape during healing.Research shows that self-tightening sutures may reduce scarring, minimize inflammatory responses, and support the natural healing process. These materials can also be biodegradable, eliminating the need for removal—especially beneficial for pediatric or geriatric patients (Figure 6) [44].

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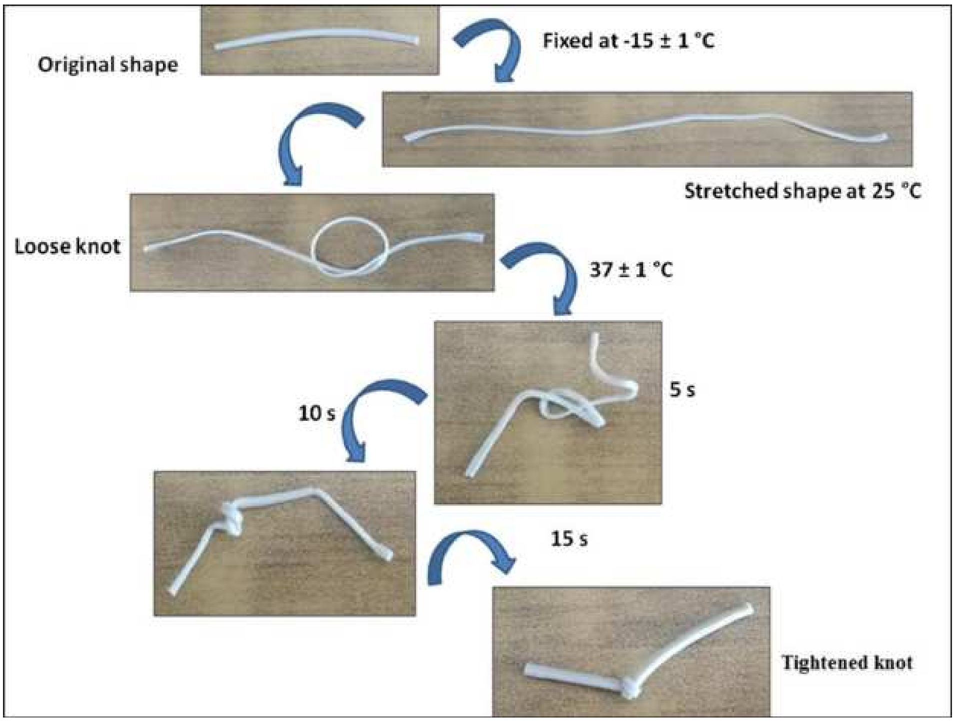

Figure 6 Self-tightening suture based on shape memory polymer activated at body temperature (37 °C)

3.4.2 Smart bandages

Beyond sutures, 4D printing is also used to create bandages that incorporate sensory layers or are made from hydrogels responsive to physiological changes such as temperature, pH, or humidity. Smart bandages can automatically release antibacterial agents upon infection detection or adjust their mechanical properties to optimize healing.

Hydrogel layers can be programmed via 4D printing to change porosity or viscosity depending on the healing phase—for example, maintaining moisture during the acute phase to promote epithelialization, and hardening later to protect the wound from external damage.

These technologies not only improve patient comfort but also enhance therapeutic efficiency, reduce healing time, and lower the risk of secondary infections [45].

4 Clinical implementation of 4D printing in medicine

Successful implementation of 4D printing in medicine requires not only technological advancements but also careful consideration of clinical aspects that determine its real-world application. This chapter focuses on key areas where 4D printing can provide therapeutic benefits, as well as the challenges that must be overcome to achieve its widespread clinical adoption.

4.1 Clinical benefits and therapeutic potential

4.1.1 Adaptive structures and biological integration

4D printing technology represents a breakthrough in medicine due to its ability to create smart structures that actively respond to physiological conditions in the body. Materials such as stimuli-responsive hydrogels and shape-memory polymers can adapt to temperature, pH, or mechanical stress. These responses improve biocompatibility, reduce the risk of complications, and enhance functional longevity of implants [1-3]. In clinical applications, implants capable of long-term interaction with surrounding tissue and active participation in healing—such as intelligent scaffolds or vascular grafts—are being tested.

4.1.2 Reduced surgical burden and reinterventions

4D printing facilitates the development of medical devices that self-expand after implantation or degrade once their function is fulfilled. Examples include self-expanding stents, growth-adaptive pediatric implants, or absorbable fixation systems. These innovations reduce the need for repeated surgeries and shorten recovery time [4-6]. Emerging applications also involve materials that release therapeutic compounds or transform their structure in response to temperature or pH without surgical intervention.

4.1.3 Personalized drug delivery

4D printing enables the development of drug formulations that respond to specific physiological stimuli. pH-sensitive capsules and temperature-activated hydrogels allow for more targeted drug release. Multilayer tablets can combine several active ingredients with staggered release times, improving treatment adherence and patient comfort [7-9]. These systems have the potential to significantly improve management of chronic conditions requiring

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tailored dosing schedules aligned with a patient's circadian rhythm.

4.1.4 Regenerative applications

4D printing is being used in regenerative medicine for tissue repair. Scaffolds produced with this technology can change stiffness, porosity, or release growth factors according to the healing phase. Applications are being explored in cartilage, nerve, skin, and liver regeneration [43]. When combined with stem cells and bioactive compounds, dynamic microsystems can enhance cell differentiation and improve vascularization in damaged tissues.

4.2 Barriers to clinical implementation

4.2.1 Material and technological limitations

The availability of biocompatible, stimuli-responsive materials remains limited. These materials often exhibit poor mechanical stability and are difficult to process. Manufacturing multi-material structures is technologically demanding and requires sophisticated equipment that is not yet standard in healthcare facilities [1,37]. Moreover, new printing protocols are needed to ensure reproducibility and precision in personalized production.

4.2.2 Regulatory and ethical challenges

Existing regulations such as MDR and FDA frameworks are not designed for programmable, individualized structures. There are no established standards for testing long-term material response, nor for ethical evaluation of autonomous material behavior. The complexity of such implants demands new approaches to informed consent and accountability for treatment outcomes [39,46]. Predicting long-term in vivo behavior increases the need for new types of clinical trials.

4.2.3 Economic and organizational barriers

Introducing 4D solutions is costly, particularly due to personalization and limited scalability. Integration into public healthcare reimbursement systems is challenging, as is coordination among developers, clinicians, and regulators [34,47]. New business models and cost-effectiveness evaluation systems are needed to capture the long-term benefits of such innovative solutions.

4.3 Outlook and recommendations for clinical adoption

In the coming years, 4D printing is expected to expand, particularly in personalized medicine and temporary implants. Key priorities include:

- development of new testing methodologies,
- legislative adaptation of regulatory frameworks,
- education of clinical personnel,
- and enhanced collaboration among research, industry, and clinical sectors [39].

Such a well-prepared environment will support the transformation of 4D printing from an experimental tool into an effective component of healthcare delivery.

5 Results and discussion

As this article is a review, the results presented here are not original experimental findings but rather a synthesis of data and conclusions reported in the existing literature. The following section highlights the most relevant outcomes of previous studies on 4D printing in biomedical engineering, with a focus on materials, techniques, and clinical perspectives.

Several studies have demonstrated that stimuli-responsive polymers and composites are central to the advancement of 4D printing. Smart materials such as shape-memory polymers (SMPs), hydrogels, and hybrid bioinks enable structures to alter their shape or properties when exposed to external triggers, including temperature, pH, light, or mechanical forces. Reported applications range from self-adjusting scaffolds in tissue engineering to minimally invasive implants and controlled drug delivery systems. These findings underscore the importance of material innovation as the foundation of successful biomedical 4D printing.

In terms of manufacturing techniques, selective laser sintering (SLS), fused deposition modeling (FDM), and direct ink writing (DIW) have been frequently adapted for 4D applications. Literature reports highlight the versatility of these methods in processing polymers, metals, and ceramics. However, scalability and reproducibility remain challenges, as many results are limited to small-scale prototypes rather than clinically applicable devices.

From a clinical perspective, pilot studies and proof-of-concept experiments suggest that 4D-printed constructs may provide significant benefits in personalized medicine. Examples include scaffolds that adapt to patient-specific anatomy, drug carriers that respond to physiological conditions, and stents that change shape after implantation. Nonetheless, long-term in vivo data are scarce, making it difficult to fully assess safety, stability, and biodegradation.

While the reviewed results demonstrate remarkable progress, several limitations persist. The availability of biocompatible and biodegradable materials is still restricted, hindering the direct translation of research into clinical practice. Moreover, reproducibility and scalability are major barriers to commercialization, as the transition from laboratory prototypes to clinical-grade products requires robust quality control. Another unresolved issue is the regulatory landscape, which lags behind technological advances and lacks clear guidelines for evaluating 4D-printed medical devices.

Interdisciplinary collaboration between material scientists, engineers, and clinicians is crucial to overcome these barriers. Ethical considerations such as patient safety, cost-effectiveness, and access to personalized treatments must also be addressed. Despite these challenges, ongoing innovations in smart polymers, bioinks, and computational design tools are expected to expand the clinical potential of 4D printing. Ultimately, the integration of stimuli-responsive materials with advanced printing techniques may reshape modern medicine by enabling adaptive, patient-specific, and functionally superior therapeutic solutions.

6 Conclusions

4D printing is an emerging and rapidly evolving field with the potential to significantly transform the future of medicine. The ability to create intelligent structures that can adapt to changing patient physiology or environmental conditions opens up new opportunities in personalized medicine, regenerative therapy, and targeted drug delivery. Although many applications remain in the experimental stage, research trends suggest that the integration of 4D printing into clinical practice is only a matter of time. Successful implementation, however, requires overcoming several technological, material, and ethical challenges. Future development will depend primarily on close collaboration among scientists, physicians, engineers, and regulators. If current barriers are addressed effectively, 4D printing could become a key tool in advancing healthcare toward greater efficiency, safety, and individualization.

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References

[1] MOMENI, F., HASSANI, S.M.M., LIU, X., NI, J.: A review of 4D printing, *Materials & Design*, Vol. 122, pp. 42-79, 2017. https://doi.org/10.1016/j.matdes.2017.02.068

[2] COMPTON, B.G., LEWIS, J.A.: 3D-Printing of Lightweight Cellular Composites, *Advanced Materials*, Vol. 26, No. 34, pp. 5930-5935, 2014. https://doi.org/10.1002/adma.201401804

[3] AHMED, A., ARYA, S., GUPTA, V., FURUKAWA, H., KHOSLA, A.: 4D printing: Fundamentals, materials, applications and challenges, *Polymer*, Vol. 228, 123926, 2021. https://doi.org/10.1016/j.polymer.2021.123926.

[4] YANG, C., TIAN, X., LIU, T., CAO, Y., LI, D.: 3D printing for continuous fiber reinforced thermoplastic composites: mechanism and performance, *Rapid Prototyping Journal*, Vol. 23, No. 1, pp. 209-215, 2017. https://doi.org/10.1108/rpj-08-2015-0098

[5] TIBBITS, S., MCKNELLY, C., OLGUIN, C., DIKOVSKY, D., HIRSCH, S.: *4D Printing and Universal Transformation*, ACADIA 14: Design Agency, Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Los Angeles, 23-25 October 2014, pp. 539-548, 2014. https://doi.org/10.52842/conf.acadia.2014.539

[6] ZHAO, T., YU, R., LI, X., CHENG, B., ZHANG, Y., YANG, X., ZHAO, X., ZHAO, Y., HUANG, W.: 4D printing of shape memory polyurethane via stereolithography, *European Polymer Journal*, Vol. 101, pp. 120-126, 2018. https://doi.org/10.1016/j.eurpolymj.2018.02.021

[7] KANG, M., PYO, Y., JANG, J.Y., PARK, Y., SON, Y.-H., CHOI, M., HA, J.W., CHANG, Y.-W., LEE, C.S.: Design of a shape memory composite(SMC) using 4D printing technology, *Sensors and Actuators A: Physical*, Vol. 283, pp. 187-195, 2018. https://doi.org/10.1016/j.sna.2018.08.049

[8] PARANDOUSH, P., LIN, D.: A review on additive manufacturing of polymer-fiber composites, *Composite Structures*, Vol. 182, pp. 36-53, 2017. https://doi.org/10.1016/j.compstruct.2017.08.088

[9] YADROITSEV, I., BERTRAND, P., SMUROV, I.: Parametric analysis of the selective laser melting process, *Applied Surface Science*, Vol. 253, No. 19, pp. 8064-8069, 2007. https://doi.org/10.1016/j.apsusc.2007.02.088

[10] BERNARD, S., KRISHNA BALLA, V., BOSE, S., BANDYOPADHYAY, A.: Compression fatigue behavior of laser processed porous NiTi alloy, *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 13, pp. 62-68, 2012. https://doi.org/10.1016/j.jmbbm.2012.04.010

[11] MARATTUKALAM, J.J., SINGH, A.K., DATTA, S., DAS, M., BALLA, V.K., BONTHA, S., KALPATHY, S.K.: Microstructure and corrosion behavior of laser processed NiTi alloy, *Materials Science and Engineering: C*, Vol. 57, pp. 309-313, 2015. https://doi.org/10.1016/j.msec.2015.07.067

[12] HALANI, P.R., KAYA, I., SHIN, Y.C., KARACA, H.E.: Phase transformation characteristics and mechanical characterization of nitinol synthesized by laser direct deposition, *Materials Science and Engineering A-structural Materials Properties Microstructure and Processing*, Vol. 559, pp. 836-843, 2013. https://doi.org/10.1016/j.msea.2012.09.031

[13] BAI, J., GOODRIDGE, R.D., HAGUE, R.J.M., SONG, M.: Improving the mechanical properties of laser-sintered polyamide 12 through incorporation of carbon nanotubes, *Polymer Engineering & Science*, Vol. 53, No. 9, pp. 1937-1946, 2013. https://doi.org/10.1002/pen.23459

[14] RIHEEN, M.A., SAHA, T.K., SEKHAR, P.K.: Inkjet Printing on PET Substrate, *Journal of The Electrochemical Society*, Vol. 166, No. 9, pp. B3036-B3039, 2019. https://doi.org/10.1149/2.0091909jes

[15] NAUROZE, S.A., NOVELINO, L., TENTZERIS, M.M., PAULINO, G.H.: *Inkjet-printed '4D' tunable spatial filters using on-demand foldable surfaces*, 2017 IEEE MTT-S International Microwave

Symposium (IMS), Honololu, HI, USA, 2017, pp. 1575-1578, 2017. https://doi.org/10.1109/mwsym.2017.8058932

[16] TIBBITS, S.: 4D Printing: Multi-Material Shape Change, *Architectural Design*, Vol. 84, No. 1, pp. 116-121, 2014. https://doi.org/10.1002/ad.1710

[17] LEIST, S.K., ZHOU, J.: Current status of 4D printing technology and the potential of light-reactive smart materials as 4D printable materials, *Virtual and Physical Prototyping*, Vol. 11, No. 4, pp. 249-262, 2016. https://doi.org/10.1080/17452759.2016.1198630

[18] LI, X., SHANG, J., WANG, Z.: Intelligent materials: a review of applications in 4D printing, *Assembly Automation*, Vol. 37, No. 2, pp. 170-185, 2017. https://doi.org/10.1108/aa-11-2015-093

[19] GONZÁLEZ-HENRÍQUEZ, C.M., SARABIA-VALLEJOS, M.A., RODRIGUEZ-HERNANDEZ, J.: Polymers for additive manufacturing and 4D-printing: Materials, methodologies, and biomedical applications, *Progress in Polymer Science*, Vol. 94, pp. 57-116, 2019. https://doi.org/10.1016/j.progpolymsci.2019.03.001

[20] PANDEY, H., MOHOL, S.S., KANDI, R.: 4D printing of tracheal scaffold using shape-memory polymer composite, *Materials Letters*, Vol. 329, No. December, 133238, 2022. https://doi.org/10.1016/j.matlet.2022.133238

[21] SIMIŃSKA-STANNY, J., NIZIOŁ, M., SZYMCZYK-ZIÓŁKOWSKA, P., BROŻYNA, M., JUNKA, A., SHAVANDI, A., PODSTAWCZYK, D.: 4D printing of patterned multimaterial magnetic hydrogel actuators, *Additive Manufacturing*, Vol. 49, 102506, pp. 1-14, 2022. https://doi.org/10.1016/j.addma.2021.102506

[22] ABDULLAH, T., OKAY, O.: 4D Printing of Body Temperature-Responsive Hydrogels Based on Poly(acrylic acid) with Shape-Memory and Self-Healing Abilities, *ACS Applied Bio Materials*, Vol. 6, No. 2, pp. 703-711, 2023. https://doi.org/10.1021/acsabm.2c00939

[23] ZU, S., ZHANG, Z., LIU, Q., WANG, Z., SONG, Z., GUO, Y., XIN, Y., ZHANG, S.: 4D printing of core–shell hydrogel capsules for smart controlled drug release, *Bio-Design and Manufacturing*, Vol. 5, No. 2, pp. 294-304, 2022. https://doi.org/10.1007/s42242-021-00175-y

[24] WANG, R., WANG, X., MU, X., FENG, W., LU, Y., YU, W., ZHOU, X.: Reducing thermal damage to adjacent normal tissue with dual thermo-responsive polymer via thermo-induced phase transition for precise photothermal theranosis, *Acta Biomaterialia*, Vol. 148, pp. 142-151, 2022. https://doi.org/10.1016/j.actbio.2022.06.007

[25] ZHAO, W., ZHANG, F., LENG, J., LIU, Y.: Personalized 4D printing of bioinspired tracheal scaffold concept based on magnetic stimulated shape memory composites, *Composites Science and Technology*, Vol. 184, No. November, 107866, 2019. https://doi.org/10.1016/j.compscitech.2019.107866

[26] YANG, G.H., KIM, W., KIM, J., KIM, G.: A skeleton muscle model using GelMA-based cell-aligned bioink processed with an electric-field assisted 3D/4D bioprinting, *Theranostics*, Vol. 11, No. 1, pp. 48-63, 2021. https://doi.org/10.7150/thno.50794

[27] DAS, A., GILMER, E.L., BIRIA, S., BORTNER, M.J.: Importance of Polymer Rheology on Material Extrusion Additive Manufacturing: Correlating Process Physics to Print Properties, *ACS Applied Polymer Materials*, Vol. 3, No. 3, pp. 1218-1249, 2021. https://doi.org/10.1021/acsapm.0c01228

[28] GE, Q., QI, H.J., DUNN, M.L.: Active materials by four-dimension printing, *Applied Physics Letters*, Vol. 103, No. 13, 131901, 2013. https://doi.org/10.1063/1.4819837

[29] MOMENI, F.M., MEHDI HASSANI, N.S., LIU, X., NI, J.: A review of 4D printing, *Materials & Design*, Vol. 122, pp. 42-79, 2017. https://doi.org/10.1016/j.matdes.2017.02.068

[30] SOLÓRZANO-REQUEJO, W., VEGA, C.A., MARTÍNEZ, R.Z., BODAGHI, M., LANTADA, A.D.: Ontology for smart 4D printed material systems and structures synergically applied with generative artificial intelligence for creativity promotion, *Smart Materials and Structures*, Vol. 34, No. 1, pp. 1-30, 2024. https://doi.org/10.1088/1361-665X/ad9dca

[31] MAHADEVAN, L., LEWIS, J.A.: Biomimetic 4D printing, *Nature Materials*, Vol. 15, No. 4, pp. 413-418, 2016. https://doi.org/10.1038/nmat4544

[32] BANDYOPADHYAY, A., BOSE, S.: *Additive manufacturing*, 2nd ed., CRC Press, 2019. https://doi.org/10.1201/9780429466236-15

[33] CHOUDHURY, S., JOSHI, A., AGRAWAL, A., NAIN, A., BAGDE, A., PATEL, A., SYED, Z.Q., ASTHANA, S., CHATTERJEE, K.: NIR-Responsive Deployable and Self-Fitting 4D-Printed Bone Tissue Scaffold, *ACS Applied Materials & Interfaces*, Vol. 16, No. 37, pp. 49135-49147, 2024. https://doi.org/10.1021/acsami.4c10385

[34] LI, Z., ZHOU, Y., LI, T., ZHANG, J., TIAN, H.: Stimuli-responsive hydrogels: Fabrication and biomedical applications, *VIEW*, Vol. 3, No. 2, 20200112, pp. 1-26, 2021. https://doi.org/10.1002/viw.20200112

[35] YU, M., BENJAMIN, M.M., SRINIVASAN, S., MORIN, E.E., SHISHATSKAYA, E.I., SCHWENDEMAN, S.P., SCHWENDEMAN, A.: Battle of GLP-1 delivery technologies, *Advanced Drug Delivery Reviews*, Vol. 130, pp. 113-130, 2018. https://doi.org/10.1016/j.addr.2018.07.009

[36] DOMÍNGUEZ-BAJO, A., ROSA, J.M., GONZÁLEZ-MAYORGA, A., RODILLA, B.L., ARCHÉ-NÚÑEZ, A., BENAYAS, E., OCÓN, P., PÉREZ, L., CAMARERO, J., MIRANDA, R.,

GONZÁLEZ, M.T., AGUILAR, J., LÓPEZ-DOLADO, E., SERRANO, M.C.: Nanostructured gold electrodes promote neural maturation and network connectivity, *Biomaterials*, Vol. 279, pp. 121186-121186, 2021. https://doi.org/10.1016/j.biomaterials.2021.121186

[37] OZBOLAT, I.T.: *3D Bioprinting Fundamentals, Principles And Applications*, Amsterdam Boston Heidelberg Academic Press, An Imprint Of Elsevier, 2017.

[38] LI, Z, ZHOU, Y., LI, T., ZHANG, J., TIAN, H.: Stimuli-responsive hydrogels: Fabrication and biomedical applications, *VIEW*, Vol. 3, No. 2, 20200112, pp. 1-26, 2021. https://doi.org/10.1002/viw.20200112

[39] ASHAMMAKHI, N., BOYER, C., PRINZET, M.: Bioinks and bioprinting technologies to make heterogeneous and biomimetic tissue constructs, *Materials Today Bio*, Vol. 1, 100008, pp. 1-23, 2019. https://doi.org/10.1016/j.mtbio.2019.100008

[40] CUI, H., ZHU, W., MIAO, S., SARKAR, K., ZHANG, L.G.: 4D Printed Nerve Conduit with *In Situ* Neurogenic Guidance for Nerve Regeneration, *Tissue Engineering Part A*, Vol. 30, No. 11-12, pp. 293-303, 2024. https://doi.org/10.1089/ten.tea.2023.0194

[41] GIBSON, I., ROSEN, D.W., STUCKER, B.: *Additive manufacturing technologies : 3D printing, rapid prototyping, and direct digital manufacturing.* New York: Springer, 2016.

[42] RAZA, A., RASHEED, T., NABEEL, F., HAYAT, U., BILAL, M., IQBAL, H.M.N.: Endogenous and Exogenous Stimuli-Responsive Drug Delivery Systems for Programmed Site-Specific Release, *Molecules*, Vol. 24, No. 6, pp. 1-21, 2019. https://doi.org/10.3390/molecules24061117

[43] MOSTAFALU, P., AKBARI, M., ALBERTI, K.A., XU, Q., KHADEMHOSSEINI, A., SONKUSALE, S.R.: A toolkit of thread-based microfluidics, sensors, and electronics for 3D tissue embedding for medical diagnostics, *Microsystems & Nanoengineering*, Vol. 2, No. 1, pp. 1-10, 2016. https://doi.org/10.1038/micronano.2016.39

[44] DUARAH, R., SINGH, Y.P., GUPTA, P., MANDAL, B.B., KARAK, N.: Smart self-tightening surgical suture from a tough bio-based hyperbranched polyurethane/reduced carbon dot nanocomposite, *Biomedical Materials*, Vol. 13, No. 4, 045004, 2018. https://doi.org/10.1088/1748-605x/aab93c

[45] FAN, Y., WANG, H., WANG, C., XING, Y., LIU, S., FENG, L., ZHANG, X., CHEN, J.: Advances in Smart-Response Hydrogels for Skin Wound Repair, *Polymers*, Vol. 16, No. 19, 2818, pp. 1-29, 2024. https://doi.org/10.3390/polym16192818

[46] SUN, X., REN, W., XIE, L., REN, Q., ZHU, Z., JIA, Q., JIANG, W., JIN, Z., YU, Y.: Recent advances in 3D bioprinting of tissues and organs for transplantation and drug screening, *Virtual and Physical Prototyping*, Vol. 19, No. 1, pp. 1-30, 2024. https://doi.org/10.1080/17452759.2024.2384662

[47] GLADMAN, A.S., MATSUMOTO, E.A., NUZZO, R.G., MAHADEVAN, L., LEWIS, J.A.: Biomimetic 4D printing, *Nature Materials*, Vol. 15, No. 4, pp. 413-418, 2016. https://doi.org/10.1038/nmat4544

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Design and technological development of robotic platforms for agricultural plant care

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Abstract: In the context of modern agricultural transformation, the integration of robotic systems into plant care is emerging as a vital solution to address challenges such as labour shortages, increased production demands, and the need for sustainable farming practices. This research focuses on the mechanical design and fabrication of a compact, modular robotic platform specifically tailored for agricultural plant care applications. The robot is designed to operate in greenhouses or open fields and is equipped with a four-wheel differential drive system, a chain transmission mechanism, and a load-distributing aluminium top plate to support essential components such as a water tank. Finite Element Analysis (FEA) was conducted to validate the structural reliability of the chassis and loadbearing elements, showing low stress and strain well below material limits, thereby ensuring operational stability and safety. A prototype was manufactured using accessible materials and methods, demonstrating the feasibility of the proposed design in terms of assembly, mobility, and structural integrity. This study contributes a mechanically robust and scalable foundation for future integration with sensors and control systems, advancing the development of smart, automated agricultural robotics.

1 Introduction

In the context of agriculture's rapid transformation toward modernization and automation, the integration of robotic technology into plant care processes has become increasingly critical [1-3]. Tasks such as pesticide spraying, weed removal, environmental monitoring, and growth assessment are labour intensive and time consuming when performed manually. Automating these stages not only addresses the growing shortage of agricultural labour but also improves operational efficiency, consistency, and sustainability in modern farming practices [4-10].

To meet these emerging demands, this research is dedicated to the mechanical design and development of a robotic system specialized for agricultural plant care. The objective is to design and fabricate a compact, modular robot capable of operating in medium to large scale environments such as greenhouses and open field farms. Emphasis is placed on a simulation-oriented prototype that enables practical validation and conceptual demonstration of the mechanical subsystems involved.

The research focuses exclusively on mechanical design, covering aspects such as chassis layout for rough terrain mobility, articulated arms for multitask functionality, and tool mounting systems for interchangeable plant care implements. Consideration is given to factors such as structural stability, ease of component integration, environmental durability, and manufacturability. The robot's frame, drive system, and end effector mechanisms are developed with a view to flexibility, enabling the robot to adapt to different crop geometries and terrain conditions.

Beyond the practical design objective, the project also serves an educational purpose providing hands on experience in mechanical design, structural analysis, and mechatronic system integration. Through this effort, the study contributes not only a working prototype but also a framework for future research in agricultural robotics focusing on mechanical design innovation.

2 Related work

Plant care robots represent a significant advancement in the application of robotics within the domain of modern agriculture. These robots are engineered to autonomously perform essential tasks such as irrigation, fertilization, environmental monitoring, and crop health assessment by measuring parameters like humidity, temperature, and soil moisture. The integration of robotic systems into plant care processes not only reduces the dependency on manual labor but also enhances the precision, consistency, and efficiency of agricultural operations.

In the context of ongoing challenges in the agricultural sector including labor shortages, rising production demands, and the need for sustainable practices plant care robots emerge as a promising technological solution. They play a pivotal role in advancing the transition toward smart, sustainable, and environmentally responsible farming. By automating repetitive and data intensive tasks, these robots contribute to increased productivity, optimized resource usage, and improved crop management, aligning with the broader goals of intelligent agricultural systems.For example, Zhang, Maoqing, et al [11] proposes two novel strategies a sliding window method and a placeholder strategy to optimize watering robot path planning and address challenges such as dimensionality and environmental variability, validated through a genetic algorithm with neighbor exchange. Amin Ghobadpour [12] discusses the emerging trends and future prospects of green energy based off road electric vehicles and autonomous robots in agriculture, highlighting their potential to address challenges such as labor shortages, energy demands, and environmental sustainability through electrification, renewable energy, and integration with advanced digital technologies. Ditzler, Lenora, and Clemens Driessen [13] investigates how robots can support agroecological farming specifically within the context of pixel cropping in the Netherlands arguing that automation in diversified, ecology based systems requires rethinking robotic design to align with agroecological values through inclusive, iterative, and hybrid approaches rather than fully replacing human labor. D Xie et.al [14] reviews the core technologies of agricultural robots operating in unstructured environments focusing on actuators, control systems, perception tools, and end effectors and highlights how their integration is driving the transition toward data driven, standardized, and unmanned smart agriculture. Fábio P. Terra et.al [15] proposes a low cost, modular robotic sprayer system using computer vision and individual nozzle control to optimize pesticide application in row crops, aiming to enhance food safety, reduce environmental impact, and provide an affordable automation solution for small and medium sized farms. Yu, Jiangfan, et al [16] develops an automatic maize seeding machine integrating sand filling, seed placement, watering, and covering, and proposes an image based evaluation method to optimize spray angle settings concluding that a 55° spray angle offers the best balance of watering efficiency, minimal seed disturbance, and uniform moisture distribution, as quantified by a novel Spray Angle Performance Index (SAPI). Fu, Qiqi, et al [17] designs an improved greenhouse self-propelled precision sprayer with a Multiple Height and Level (MHL) rack and advanced sensing technologies, demonstrating that it offers greater spray uniformity and operational stability compared to traditional systems, while also highlighting its precision and cost-saving potential through comparative analysis. Luo Y et.al [18] proposes a suspended rail automatic variable distance spray system for solar greenhouses, which uses laser sensing and real time control to optimize nozzle positioning for vertically cultivated crops demonstrating a 16.65% increase in pesticide adherence and a 29.58% reduction in pesticide use compared to fixed-distance spraying, thereby enhancing precision, efficiency, and environmental sustainability. Yao, Zhixin et.al [19] reviews and compares existing research on autonomous navigation and path planning technologies for agricultural machinery, categorizing key methods such as GNSS, machine vision, and LiDAR, detailing 22 algorithms across four planning approaches, and highlighting unresolved challenges and future research directions to enhance obstacle avoidance and path optimization. Wang, Yue, et al [20] develops an intelligent wall mortar spraying robot featuring a retractable structure for extended working range, laser based parallel adjustment, and LiDAR driven area recognition, demonstrating its ability to autonomously align with walls, avoid non spray zones, and effectively perform automated spraying with high accuracy and efficiency. Given the diversity of robotic applications and the advancements in precision agricultural technologies reviewed above, it is evident that plant care robotics holds substantial potential to address critical challenges in modern farming. Therefore, this research was conducted to contribute a specialized mechanical design solution tailored to the needs of plant care automation, aiming to enhance operational efficiency, adaptability, and sustainability in smart agriculture systems.

3 Mechanical design architecture

3.1 Overall structural design

The proposed plant care robot features a compact, modular frame constructed primarily from aluminium extrusion profiles, providing both structural integrity and design flexibility. The overall dimensions of the robot are 560 mm (length) × 410 mm (width) × 220 mm (height), making it suitable for navigating narrow crop rows or greenhouse aisles. The platform accommodates a 5-10 kg water tank, centrally positioned for balanced load distribution.

A four-wheel configuration is used to ensure mobility and ground stability, with robust rubberized wheels designed for semi-structured terrains. The drivetrain utilizes two chain-driven systems connected to stepper motors for independent left right wheel control, enabling differential steering. The chains are tensioned and guided by sprockets mounted on both motor shafts and wheel axles to ensure synchronized movement and torque transmission (Figure 1).

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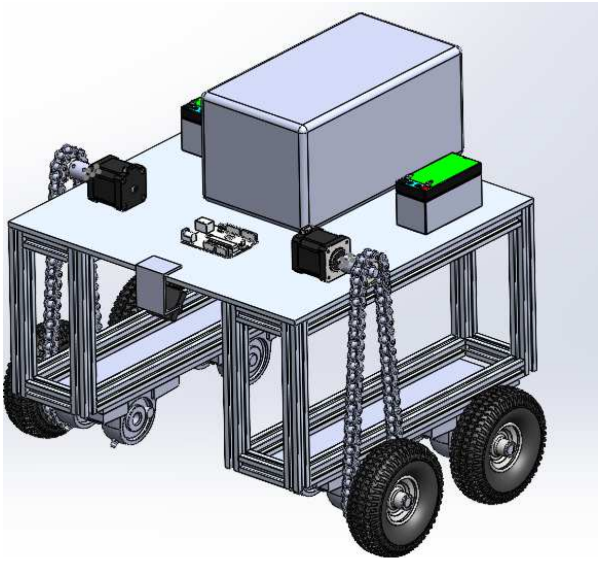

Figure 1 Mechanical design overview of the plant care robot platform

The gap between the two supporting leg frames is 200 mm, allowing the system to straddle over narrow crops or rows, minimizing interference with the plants during operation. The top surface supports electronics and power systems (not shown), while the bottom region remains accessible for future integration of spraying arms, sensing modules, or robotic manipulators.

3.2 Chassis and frame design

The chassis of the plant care robot is designed with a focus on modularity, lightweight construction, and adaptability to semi-structured agricultural environments. The entire frame is fabricated using 20×20 mm 6063-T5 aluminium profiles, chosen for their excellent balance of strength to weight ratio, corrosion resistance, and ease of machining and assembly. The use of extruded aluminium allows for future component integration and structural adjustments without requiring welding or cutting, enhancing maintainability.

The robot's overall frame structure consists of three main segments:

Central support platform (footrest): measuring 105 mm (height) × 400 mm (length) × 200 mm (width), serves as the mechanical core for mounting electronic components and the water tank (5-10 kg capacity).

Side legs: symmetrically positioned with a 200 mm gap between them to straddle plant rows without disturbing crops.

Small connecting frame: sized 200 mm × 240 mm, reinforces lateral stability and provides a mounting base for drive systems or sensor modules.

The top frame layout, as shown in Figure 2 includes transverse beams to support both mechanical loads and modular attachments such as spraying arms or vision systems. The frame's open design allows air circulation around electronic components and provides access for maintenance.

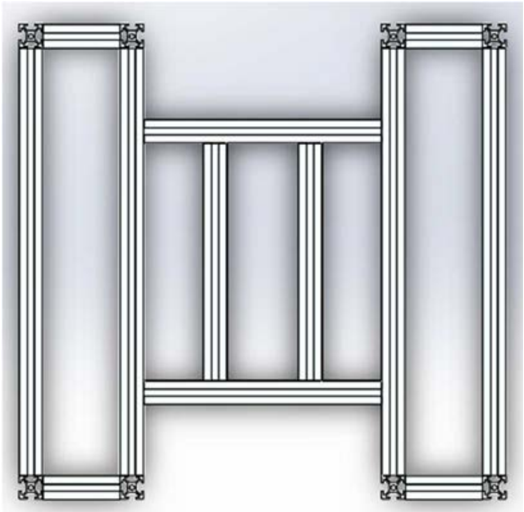

Figure 2 Chassis and frame design

This compact aluminium-based frame design ensures the robot remains both structurally stable and lightweight, meeting the mobility and load bearing requirements of medium to large scale plant care applications in greenhouses or open fields.

To evaluate the mechanical reliability of the top platform under operational loads, a finite element analysis (FEA) was conducted. The simulation assesses the von Mises stress distribution across a 6 mm thick 6061-T6 aluminium plate mounted on the frame and subjected to a uniform load of approximately 70 N, representing the weight of components such as the water tank and electronics.

As shown in Figure 3, the von Mises stress values across the structure range from 83.7 Pa to 57.9 kPa, with stress concentrations observed near the plate corners—likely due to localized boundary conditions or fixed constraints. Importantly, the maximum stress value ($\approx 5.8 \times 10^4$ N/m²) is significantly lower than the material's yield strength of 275 MPa (2.75×10^8 N/m²) for 6061-T6 aluminium. This indicates a very high safety factor, confirming that the platform will remain within the elastic deformation range and not experience plastic deformation or failure under normal operating conditions.

The results validate the design decision to use 6061-T6 for the top plate and confirm the adequacy of the supporting 6063-T5 aluminium frame. The system is structurally sound for the expected loading, ensuring durability and stability during field operation.

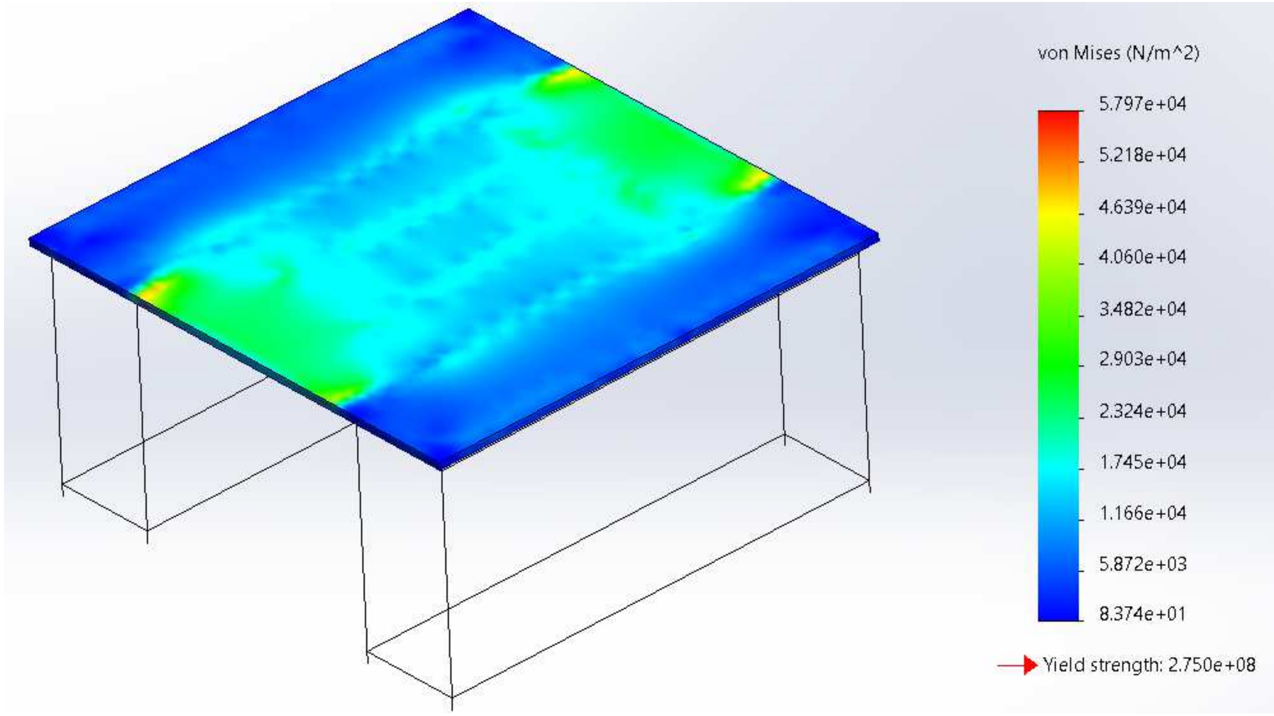

Figure 3 The von Mises stress distribution from frame

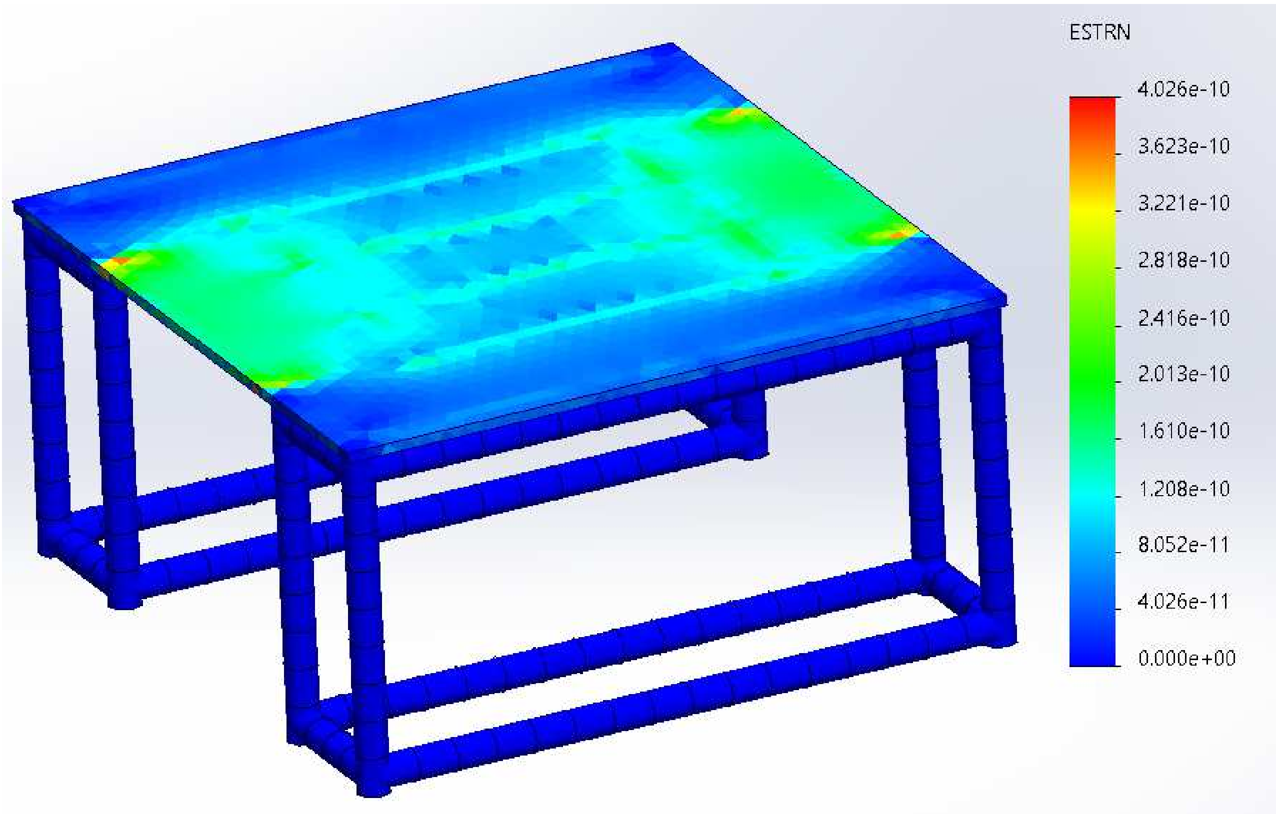

Figure 4 The equivalent strain (ESTRN) across the frame

To complete the structural validation, a strain analysis was performed under the same loading and boundary conditions used in the previous stress and displacement simulations. The plot in Figure 4 illustrates the distribution of equivalent strain (ESTRN) across the frame and top aluminium plate.

The results indicate extremely low strain values throughout the structure, with peak strain reaching approximately 4.03×10^{-10}. These values are orders of magnitude below typical strain thresholds for structural deformation in 6061-T6 and 6063-T5 aluminium, confirming that the entire chassis and load-bearing plate remain well within the elastic deformation range.

Strain concentrations are mildly visible at the corners of the plate corresponding with locations of stress accumulation, but these are still negligible in magnitude. The rest of the frame exhibits near-zero strain, which aligns with expectations given the lightweight loading scenario (~70 N) and the material stiffness.

These results further validate that the current mechanical design ensures durability, elastic recovery, and structural safety, with no risk of plastic deformation or fatigue under nominal operational loads.

4 Results and discussion

All in-text citations should be listed in the reference list at the end of your document (Figure 2, Figure 3).

Following the completion of the mechanical design and structural validation, a full-scale prototype of the plant care robot was fabricated and assembled, as shown in Figure 5. The development and assembly of the agricultural plant care robot prototype were carried out in strict accordance with the proposed mechanical design specifications, resulting in a structurally accurate and functionally stable system. The chassis was constructed using 20×20 mm 6063-T5 aluminium extrusion profiles, chosen for their excellent mechanical properties, corrosion resistance, and ease of assembly. These lightweight yet durable components formed the skeleton of the robot, offering high structural integrity and modularity. To address concentrated loading and enhance structural performance, a 6 mm thick 6061-T6 aluminium plate was mounted on the top surface of the frame. This plate acted as a load distribution platform, accommodating an estimated operational payload of 70 N, which includes the water tank (up to 10 kg), drive components, and potential sensor modules. Under static loading conditions, the prototype maintained its shape with no visible signs of deformation, deflection, or instability, demonstrating its robustness and suitability for semi-structured agricultural environments such as narrow crop rows or greenhouse aisles.

To further evaluate mechanical performance, finite element analysis (FEA) was conducted to simulate structural behaviour under loading. The von Mises stress analysis revealed that the maximum stress was approximately 57.9 kPa, located near the corner constraints of the aluminium plate. This value is significantly lower than the yield strength of 275 MPa for 6061-T6 aluminium, providing a substantial margin of safety and confirming the structure's ability to operate under normal agricultural conditions without risk of yielding or failure. Strain analysis (ESTRN) further indicated minimal deformation, with peak strain values around 4.03×10^{-10}, which is orders of magnitude below the elastic threshold, thus confirming that the materials remain well within the elastic range throughout operation. These results validate the choice of materials and confirm the adequacy of the load-bearing structure in terms of stiffness, strength, and long-term reliability.

The displacement simulation showed a smooth distribution of deflection, with the maximum occurring at unsupported plate edges. Although some exaggerated values appeared due to mesh density or improperly constrained boundary conditions in the simulation software, the physical prototype showed no noticeable warping, tilting, or deflection during preliminary loading and mobility tests. Observations from manual push tests confirmed the frame's resistance to torsion and bending, reinforcing confidence in its use on uneven terrain with minor vibrational loads.

The mobility system, consisting of four wheels and a chain-driven differential mechanism, also underwent design verification and theoretical performance evaluation. The drivetrain was built using 04C chain and sprocket components, with a gear ratio of 2:5 achieved through a 12-tooth sprocket on the motor and a 30-tooth sprocket on the drive axle. This configuration effectively reduces wheel rotation speed while increasing torque by 2.5 times, making it suitable for agricultural use where high torque and low speed are prioritized over rapid motion. Calculations show that, with the selected motors (JGB37 series), the output torque at the wheel can reach over 2 Nm per motor, generating a combined tractive force of approximately 63.7 N, which is sufficient to move a 20 kg load under typical rolling resistance conditions. While the motors used in the current prototype were simulation units, the drivetrain demonstrated consistent alignment and tension, with the chain remaining engaged and responsive under test movement. Minor irregularities such as chain lag or stalling were observed, primarily due to insufficient motor power in the prototype, which will be addressed in future iterations by integrating higher power geared motors.

In summary, the prototype exhibited excellent compliance with mechanical and structural expectations. The modular design enables easy disassembly and upgradeability, the fabricated frame is lightweight and mechanically sound, and the system is well-suited for integration with additional components such as sensors, actuators, and control electronics. The FEA results, supported by physical observations, indicate that the current mechanical structure can confidently support further development toward full automation. This validation provides a solid foundation for advancing the project to the next phase, including control integration, sensor-based perception, and autonomous plant care functionalities.

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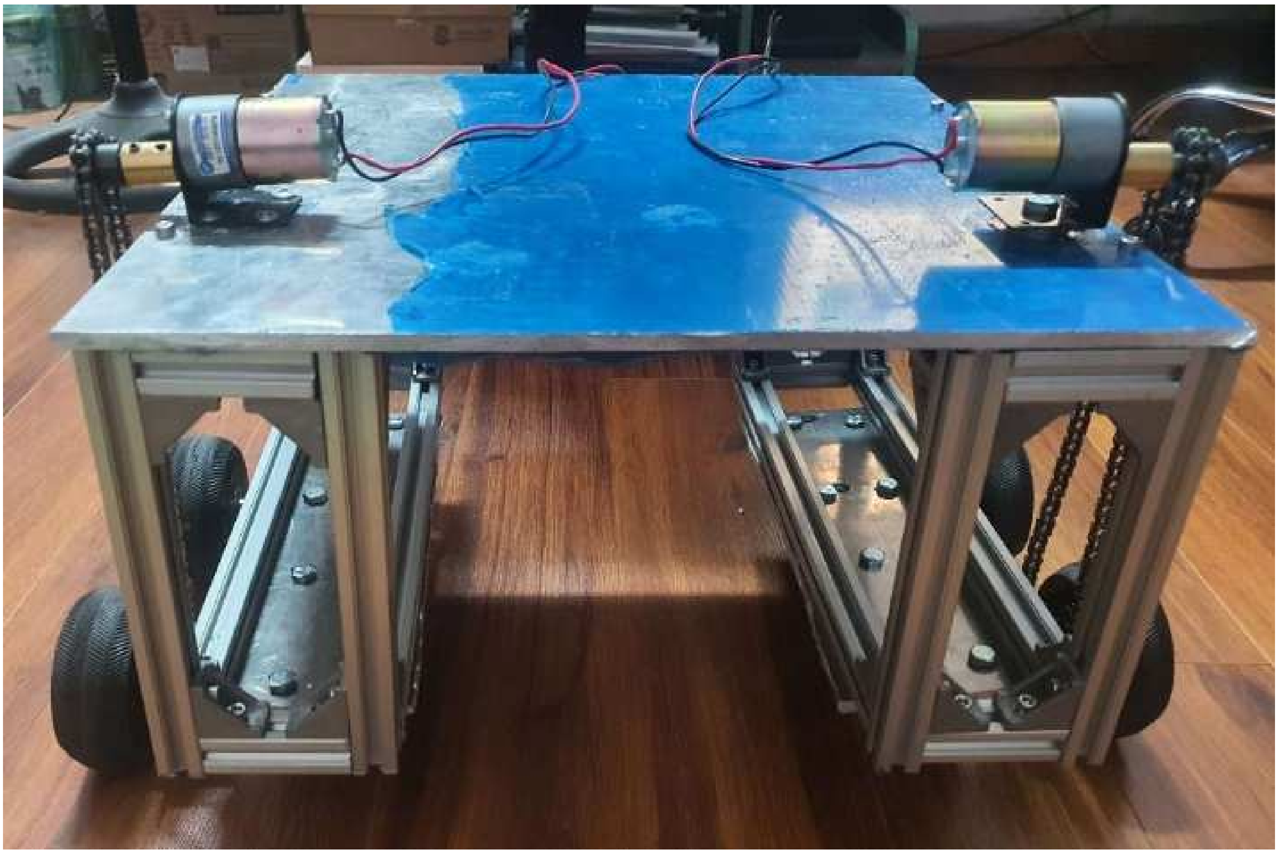

Figure 5 A full-scale prototype of the plant care robot

5 Conclusions

This study successfully designed, analysed, and fabricated a mechanical prototype of a robotic platform intended for plant care applications in agriculture. By focusing exclusively on mechanical architecture, the project established a robust and modular frame constructed from 6063-T5 aluminium profiles, combined with a 6 mm thick 6061-T6 aluminium plate for load distribution. Key mechanical subsystems, including a differential drive system with chain transmission and a compact wheelbase, were developed to support operation in structured environments such as greenhouses and narrow crop rows. Finite Element Analysis (FEA) confirmed the structural integrity of the design under operational loads, with stress and strain levels significantly below the yield limits of the materials used. The physical prototype was assembled using accessible manufacturing techniques and materials, validating the design's manufacturability, rigidity, and ease of assembly.

Building upon the successful development of the mechanical prototype, future work will focus on transforming the platform into a fully autonomous and intelligent agricultural robot. This includes integrating sensor systems such as soil moisture sensors, ultrasonic or LiDAR modules, and environmental monitors to enable real-time interaction with crop conditions. A control system based on microcontrollers (e.g., Arduino or Raspberry Pi) will be implemented to manage motor control, process sensor data, and execute plant care routines. In addition, the robot's navigation capabilities will be enhanced through the application of GPS, vision-based tracking, or predefined path planning to ensure precise movement within crop rows or greenhouse environments. Modular end-effectors for watering, spraying, and crop monitoring will also be designed for quick attachment and task flexibility. Finally, efforts will be made to improve energy efficiency and sustainability, including exploring the use of solar panels for outdoor operation. These advancements aim to transform the current mechanical platform into a smart, adaptable, and scalable solution for modern agriculture.

References

[1] AMPATZIDIS, Y., DE BELLIS, L., LUVISI, A.: iPathology: Robotic Applications and Management of Plants and Plant Diseases, *Sustainability*, Vol. 9, No. 6, 1010, pp. 1-14, 2017. https://doi.org/10.3390/su9061010

[2] ATEFI, A., GE, Y., PITLA, S., SCHNABLE, J.: Robotic Technologies for High-Throughput Plant Phenotyping: Contemporary Reviews and Future Perspectives, *Frontiers in Plant Science*, Vol. 12, No. June, 611940, pp. 1-18, 2021. https://doi.org/10.3389/fpls.2021.611940

[3] CHENG, C., FU, J., SU, H., REN, L.: Recent Advancements in Agriculture Robots: Benefits and

Challenges, *Machines*, Vol. 11, No. 1, 48, pp. 1-24, 2023. https://doi.org/10.3390/machines11010048

[4] HAFEEZ, A., HUSAIN, M.A., SINGH, S.P., CHAUHAN, A., KHAN, M.T., KUMAR, N., CHAUHAN, A., SONI, S.K.: Implementation of drone technology for farm monitoring & pesticide spraying: A review, *Information processing in Agriculture*, Vol. 10, No. 2, pp. 192-203, 2023. https://doi.org/10.1016/j.inpa.2022.02.002

[5] HEJAZIPOOR, H., MASSAH, J., SORYANI, M., VAKILIAN, K.A., CHEGINI, G.: An intelligent spraying robot based on plant bulk volume, *Computers and Electronics in Agriculture*, Vol. 180, No. January, 105859, 2021. https://doi.org/10.1016/j.compag.2020.105859

[6] NGUYEN, V.-T., TUNG, T.T.: Development of a prototype of weeding robot, *Engineering Research Express*, Vol. 6, No. 1, 015411, pp. 1-14, 2024. https://doi.org/10.1088/2631-8695/ad3403

[7] LI, Y., GUO, Z., SHUANG, F., ZHANG, M., LI, X.: Key technologies of machine vision for weeding robots: A review and benchmark, *Computers and Electronics in Agriculture*, Vol. 196, No. May, 106880, 2022. https://doi.org/10.1016/j.compag.2022.106880

[8] OLIVEIRA, L.F.P., MOREIRA, A.P., SILVA, M.F.: Advances in Forest Robotics: A State-of-the-Art Survey, *Robotics*, Vol. 10, No. 2, 53, pp. 1-20, 2021. https://doi.org/10.3390/robotics10020053

[9] HALDER, S., AFSARI, K.: Robots in Inspection and Monitoring of Buildings and Infrastructure: A Systematic Review, *Applied Sciences*, Vol. 13, No. 4, 2304, pp. 1-37, 2023. https://doi.org/10.3390/app13042304

[10] JIN, Y., LIU, J., XU, Z., YUAN, S., LI, P., WANG, J.: Development status and trend of agricultural robot technology, *International Journal of Agricultural and Biological Engineering*, Vol. 14, No. 4, pp. 1-19, 2021. https://doi.org/10.25165/j.ijabe.20211404.6821

[11] ZHANG, M., GUO, W., WANG, L., LI, D., HU, B., WU, Q.: Modeling and optimization of watering robot optimal path for ornamental plant care, *Computers & Industrial Engineering*, Vol. 157, No. July, 107263, 2021. https://doi.org/10.1016/j.cie.2021.107263

[12] GHOBADPOUR, A., MONSALVE, G., CARDENAS, A., MOUSAZADEH, H.: Off-Road Electric Vehicles and Autonomous Robots in Agricultural Sector: Trends, Challenges, and Opportunities, *Vehicles*, Vol. 4, No. 3, pp. 843-864, 2022. https://doi.org/10.3390/vehicles4030047

[13] DITZLER, L., DRIESSEN, C.: Automating Agroecology: How to Design a Farming Robot Without a Monocultural Mindset?, *Journal of Agricultural and Environmental Ethics*, Vol. 35, 2, pp. 1-31, 2022. https://doi.org/10.1007/s10806-021-09876-x

[14] XIE, D., CHEN, L., LIU, L., CHEN, L., WANG, H.: Actuators and Sensors for Application in Agricultural Robots: A Review, *Machines* Vol. 10, No. 10, 913, pp. 1-31, 2022. https://doi.org/10.3390/machines10100913

[15] TERRA, F.P., NASCIMENTO, G.H.D., DUARTE, G.A., DREWS-JR, P.L.: Autonomous Agricultural Sprayer using Machine Vision and Nozzle Control, *Journal of Intelligent & Robotic Systems*, Vol. 102, 38, pp. 1-18, 2021. https://doi.org/10.1007/s10846-021-01361-x

[16] YU, J., ZHANG, Z., LIU, X., CHEN, K., LI, Y., IGATHINATHANE, C., WANG, X., ZHANG, M., LI, H., HA, T.: Automatic maize seeding machine watering spray angle determination by using a novel index, *Computers and Electronics in Agriculture*, Vol. 224, No. September, 109234, 2024. https://doi.org/10.1016/j.compag.2024.109234

[17] FU, Q., LI, X., ZHANG, G., MA, Y.: Improved greenhouse self-propelled precision spraying machine—multiple height and level (MHL) control, *Computers and Electronics in Agriculture*, Vol. 201, No. October, 107265, 2022. https://doi.org/10.1016/j.compag.2022.107265

[18] LUO, Y., HUANG, D., JIANG, P., XIANG, S., LIU, J., XU, M., SHI, Y.: Design and Experimental Testing of an Overhead Rail Automatic Variable-Distance Targeted Spray System for Solar Greenhouses, *Agriculture*, Vol. 13, No. 9, 1853, pp. 1-17, 2023. https://doi.org/10.3390/agriculture13091853

[19] YAO, Z., ZHAO, C., ZHANG, T.: Agricultural machinery automatic navigation technology, *iScience*, Vol. 27, No. 2, 108714, pp. 1-20, 2024. https://doi.org/10.1016/j.isci.2023.108714

[20] WANG, Y., XIE, L., WANG, H., ZENG, W., DING, Y., HU, T., HU, J.: Intelligent spraying robot for building walls with mobility and perception, *Automation in Construction*, Vol. 139, No. July, 104270, 2022. https://doi.org/10.1016/j.autcon.2022.104270

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Mechanical testing of 3D printed samples made of flexible TPU material

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Keywords: TPU, 3D printing, Fused Deposition Modeling, mechanical testing.
Abstract: This scientific article deals with the mechanical testing of samples produced by 3D printing technology from thermoplastic polyurethane (TPU), which is a flexible polymer with elastomeric properties. The aim of the study was to evaluate the mechanical behaviour of TPU material under different printing parameters and loads, especially in compression. The samples were printed using the FDM (Fused Deposition Modeling) method with variable settings such as layer orientation, infill, layer thickness and printing speed, while a standardized shape of test specimens according to ISO 604 was used. Testing revealed a significant dependence of mechanical properties on layer orientation and infill degree. TPU showed high elasticity and energy absorption capacity, which confirms its potential for applications where flexibility, shock absorption and shape adaptability are required. The results point to the importance of optimizing printing parameters to achieve the desired mechanical properties in practice.

1 Introduction

With the increasing availability of 3D printing, flexible polymers such as TPU are becoming increasingly popular in applications requiring flexibility, impact resistance and repeated deformability. TPU combines the properties of plastic and rubber and is suitable for the production of components such as seals, damping elements and wearable devices. However, due to the anisotropic nature of FDM technology, the mechanical behaviour of TPU samples is strongly influenced by printing parameters, which requires their systematic evaluation. Mechanical testing of 3D printed samples made of flexible TPU thermoplastic polyurethane (Figure 1) is a key step in evaluating their functional properties and reliability in real-world applications. TPU is a material known for its flexibility, abrasion resistance, toughness, and shock absorption, making it suitable for use in a variety of industries, from automotive to footwear to medical and consumer products. However, its exceptional properties also place specific demands on the manufacturing and testing of mechanical properties, especially when used in additive manufacturing [1]. 3D printing, specifically Fused Deposition Modeling (FDM) technology, enables the rapid and cost-effective production of TPU parts with various geometric configurations and internal structures. These parameters have a significant impact on the resulting mechanical properties of the samples, such as tensile strength, elasticity, hardness, tear resistance, and fatigue strength. In addition, the layering direction, layer height, filling structure and nozzle temperature during printing are among the factors that can significantly affect the quality and consistency of prints [2]. Therefore, it is essential to take these variables into account when designing experiments and interpreting test results. The goal of mechanical testing of TPU samples is not only to quantify their basic physical and mechanical characteristics, but also to understand how the material behaviour changes depending on the technological conditions of printing and the type of load. Testing includes pressure tests that simulate repeated stress in practical use [3]. The results of these tests serve as a basis for optimizing production parameters, designing functional components and improving predictive models of TPU behaviour under various operating conditions. Given the increasing use of flexible materials in 3D printing, it is important to deepen knowledge about their mechanical behaviour and reliability [4-6]. Mechanical testing thus represents not only a scientific approach to evaluating material properties, but also a practical tool for developing innovative products that must meet demanding requirements for performance, durability and safety [7].

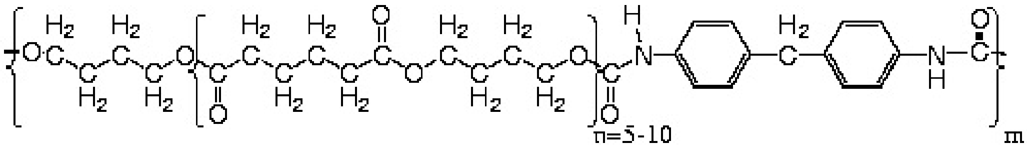

Figure 1 Molecular structure of thermoplastic polyurethanes [1]

2 3D printing of samples

2.1 Proposal for a methodology for testing materials

The samples were designed in the Simplyfy3D program according to the standards. The ISO 604 standard from 2002 was established for the pressure test. After designing the sample, we generated a good for the following 3D printing. In Figure 2 we can see the sample design before printing for the pressure test.

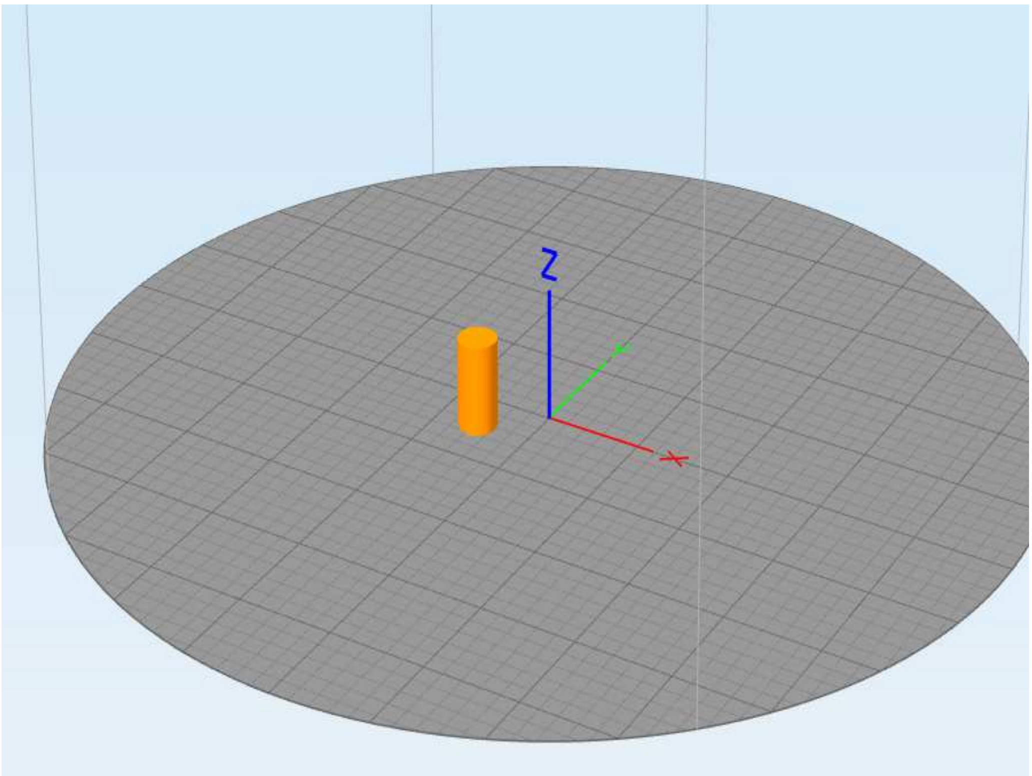

Figure 2 Sample design for static pressure test

2.2 3D printing of samples

3D printing of the samples was carried out in the laboratory on a Trilab DeltiQ 2 3D printer. For 3D printing of the samples, a Nimble extruder had to be used due to the TPU material we used to print the samples.

Before starting the print, we set the printing parameters. The Trilab DeltiQ 2 is a printer with a working area of Ø 250 mm (X,Y) x 300 mm (Z). We used a Nimble extruder, for which we set the nozzle diameter to 0.40 mm and the extrusion width to 0.40 mm. For the layer, we had to enter parameters for the height of the primary layer, which was 0.20 mm. Then we set the direction of the contour, which was made from the outside to the bottom. We set the parameters for the height of the first layer to 150%, the width of the first layer to 100% and the speed of the first layer to 50%. We also set the starting point closest to the specific location, namely X to -200.0 mm and Y to 200.0 mm. For the infill, we entered the parameters for the inner infill to 50%/75%/100%, the contour overlaps to 25%, the infill extrusion width to 150% and the minimum infill length to 1 mm. We set the substrate temperature to 200 °C. and the static speed of the supporting structure to 80%, the insufficient speed of the solid infill to 100%, the speed of movement of the X/Y and Z axes to 9000 mm/min. In Figure 3 we can see the 3D printing of the samples and its final printing. Subsequently, in Figure 4 there are printed samples for the pressure test with 50%, 75% and 100% infill.

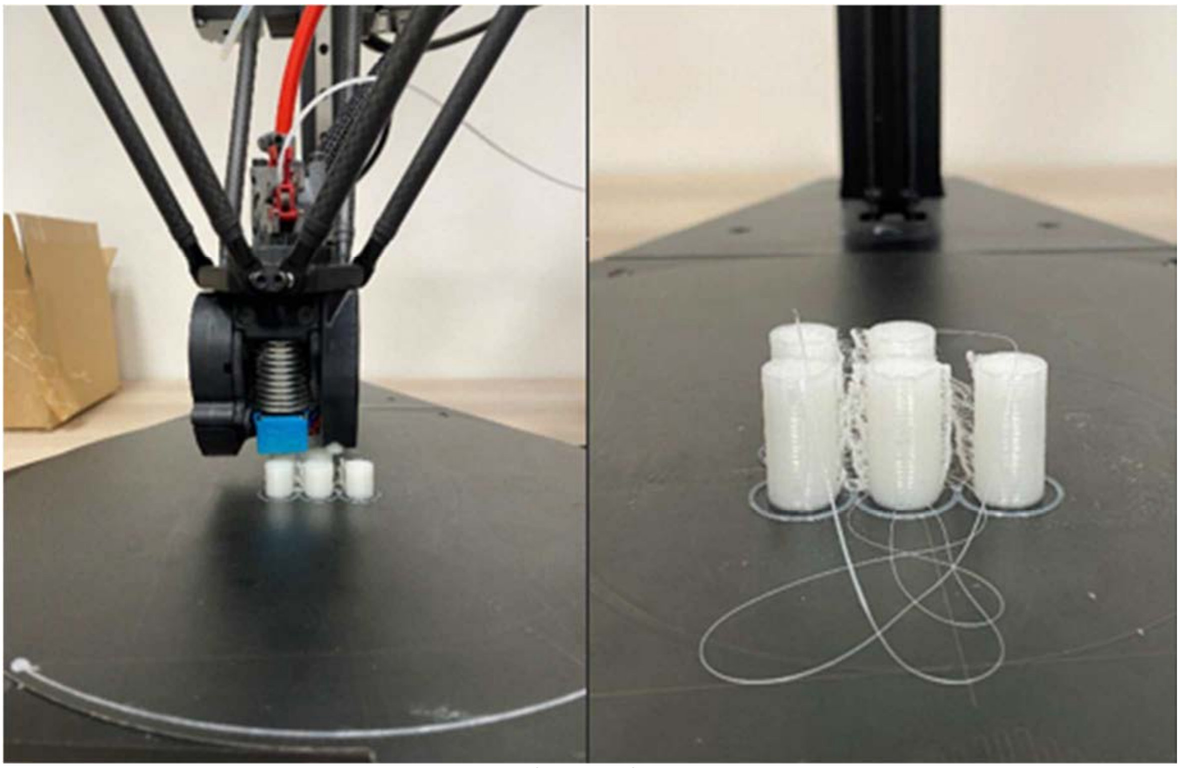

Figure 3 3D printing of samples for static pressure testing

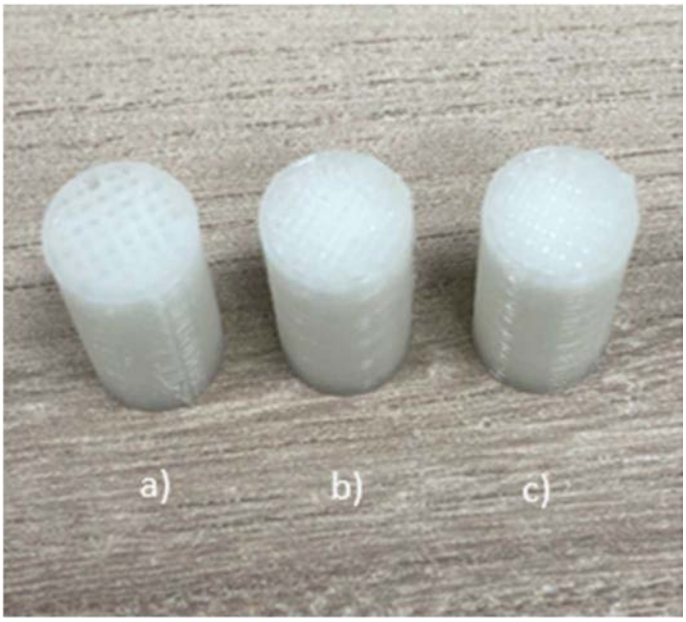

Figure 4 Samples for static pressure test a) 50% infill b) 75% infill c) 100% infill

3 Mechanical testing, evaluation of pressure tests

Using compression tests, we investigated the deformation behaviour of the material and the conditions of external forces. For mechanical testing, a simple cylinder was printed, the dimensions of which were determined according to the ISO 604 standard from 2002, which describes methods for determining the compression properties of plastics. The samples were printed from TPU material with 50%, 75% and 100% infill. The compression test was carried out on the Inspect 5 testing device, where the tested sample was inserted between the jaws (Figure 5).

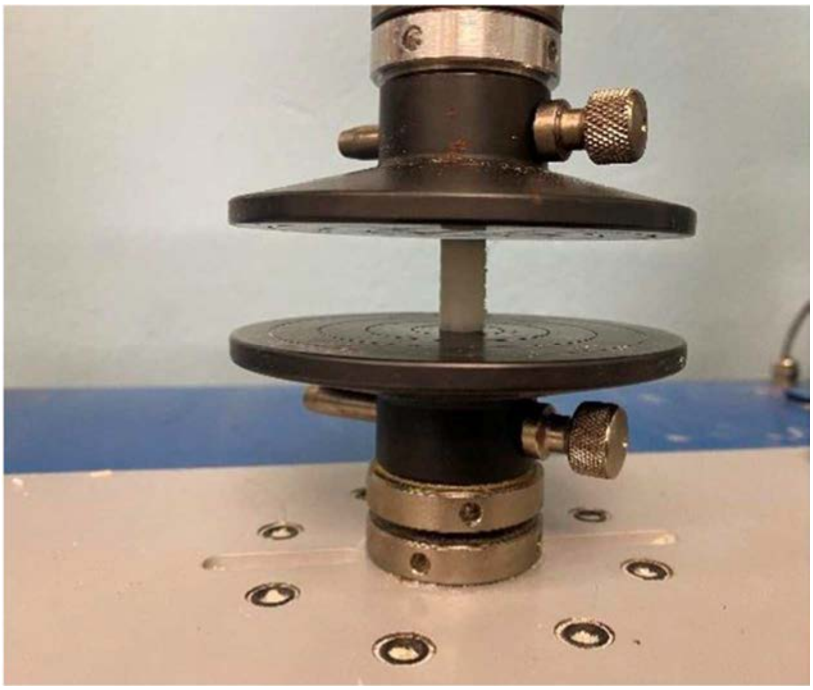

Figure 5 Test sample inserted between jaws

The output of the testing device was a data table. The following figures show graphs that describe the deformation on the X-axis and the pressure in megapascals on the Y-axis. From the graphic representation in Figure 6, we can assess that the samples have low resistance to pressure and pass into the deformation region. It follows that the material has the ability to withstand compressive forces reducing the infill cross-section.

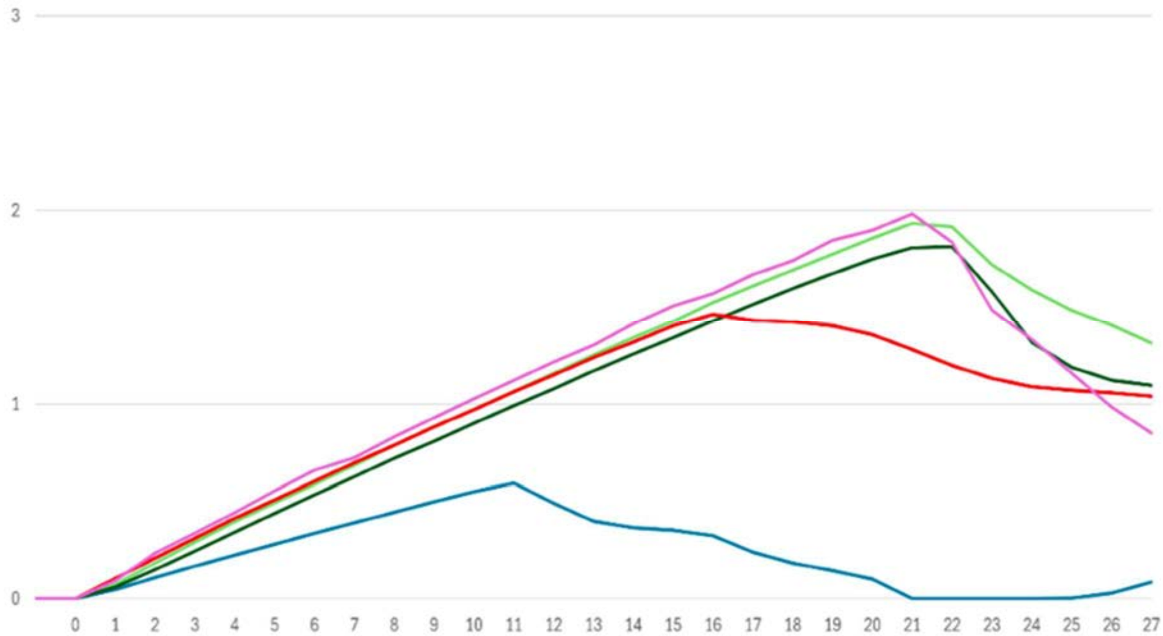

Figure 6 Graphical representation of compression test for TPU material with 50% infill

From the graphic representation in Figure 7 we can assess that the linear region is approximately the same for all the tested samples. The region of plastic deformation is indicated on the graph when it is gradually compressed without interruption of the material. From the graphic representation it follows that the material has the ability to resist compressive forces reducing the cross-section of the infill.

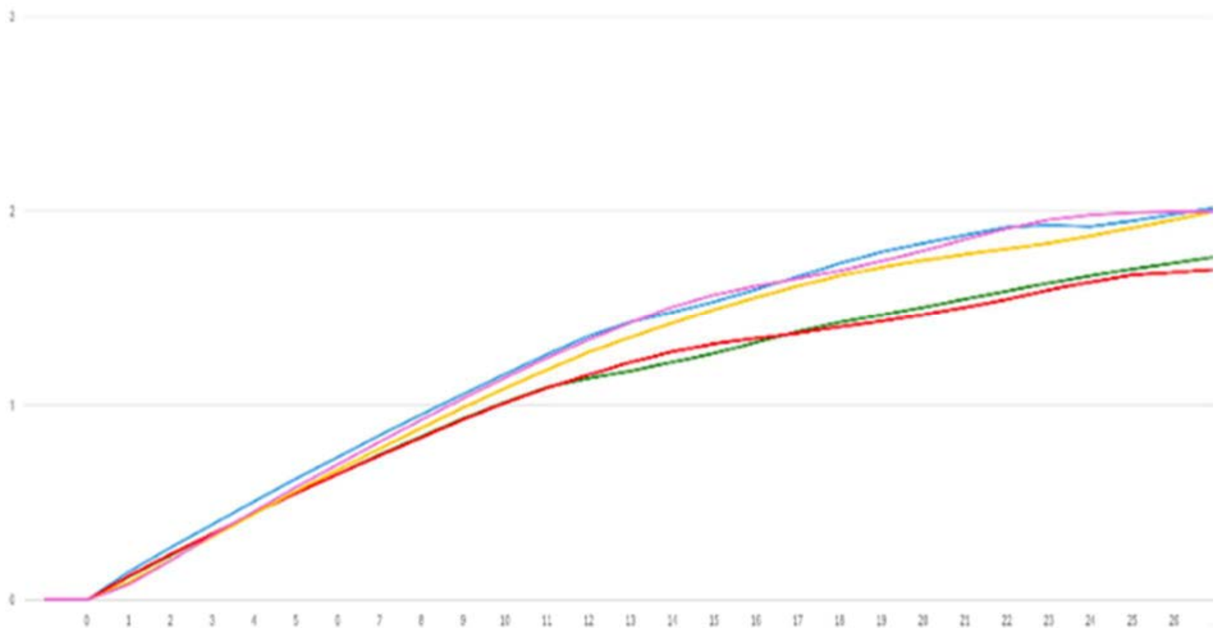

Figure 7 Graphical representation of compression test for TPU material with 75% infill

In Figure 8 we can observe very similar behaviour as in the previous testing.

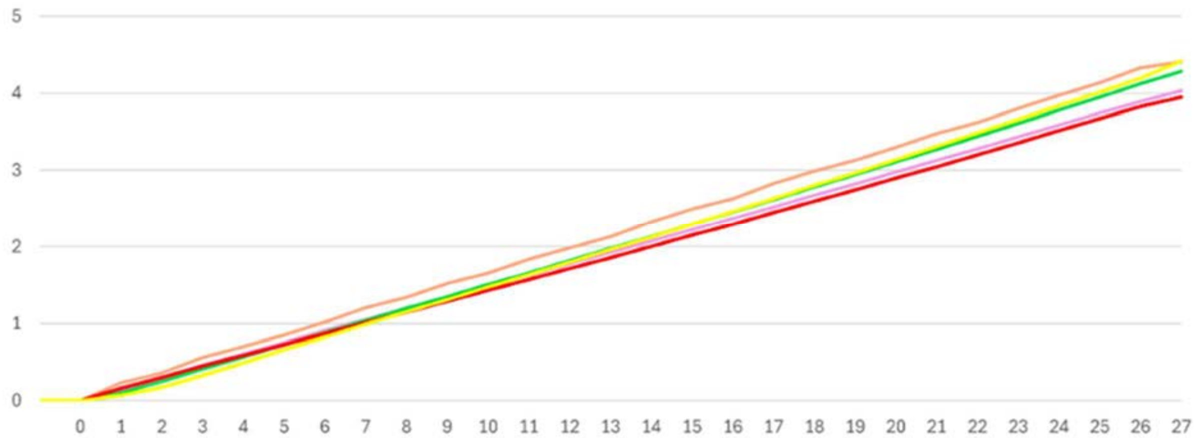

Figure 8 Graphical representation of compression test for TPU material with 100% infill

4 Conclusion

This scientific research provides an insight into the field of testing flexible TPU, where compression tests were performed on cylindrical samples with 50%, 75% and 100% infill. Compression testing of 3D printed samples of flexible TPU is a key step in verifying their mechanical properties, reliability and functional behaviour in real-world conditions. The results of these tests provide a deeper understanding of how the material behaves under load, how it deforms and whether it can maintain its integrity after repeated or long-term pressure. Flexible materials such as TPU are increasingly used in technical applications where a combination of flexibility, strength and wear resistance is required – whether it is for damping elements, protective components, soft joints or functional prototypes. From an experimental point of view, the testing has shown that the quality and set infill of 3D printing significantly affects the behaviour of TPU material under load. The findings suggest that TPU as a 3D printing material has great potential in areas where flexibility and durability are needed. The pressure testing also highlighted the need for a comprehensive evaluation not only of the material itself, but also of the way the object is designed and printed. The results of these tests can serve as a basis for further research and development aimed at optimizing the design of 3D printed components from flexible materials, thereby expanding their application in various industrial and consumer areas.

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References

[1] AHMAD, M., JAVAID, M., HALEEM, A.: A study on fused deposition modeling (FDM) and laser-based additive manufacturing (LBAM) in the medical field, *Intelligent Pharmacy*, Vol. 2, No. 3, pp. 381-391, 2024. https://doi.org/10.1016/j.ipha.2024.02.010
[2] SHASKIKUMAR, S., SREEKANTH, M.S.: The effect of printing parameters on tensile properties of thermoplastics prepared by fused deposition modeling (FDM) based additive manufacturing technique, *Materials Today: Proceedings,* Vol. 90, Part 1, pp. 256-261, 2023. https://doi.org/10.1016/j.matpr.2023.06.212
[3] NGO, T.D., KASHANI, A., IMBALZANO, G., NGUYEN, K.T.Q., HUI, D.: Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, *Composites Part B: Engineering*, Vol. 143, pp. 172-196, 2018. https://doi.org/10.1016/j.compositesb.2018.02.012
[4] WONG, V.K., HERNANDEZ, A.: A Review of Additive Manufacturing, *International Scholarly Research Notices*, Vol. 2012, 208760, pp. 1-10, 2012. https://doi.org/10.5402/2012/208760
[5] SHAIKH, A., JAMDADE, B., CHANDA, A.: Effects of Customized 3D-Printed Insoles in Patients with Foot-Related Musculoskeletal Ailments—A Survey-Based Study, *Prosthesis*, Vol. 5, No. 2, pp. 550-561, 2023. https://doi.org/10.3390/prosthesis5020038
[6] CADDEO, S., BOFFITO, M., SARTORI, S.: Tissue Engineering Approaches in the Design of Healthy and Pathological In Vitro Tissue Models, *Frontiers in Bioengineering and Biotechnology*, Vol. 5, 40, pp. 1-22, 2017. https://doi.org/10.3389/fbioe.2017.00040
[7] HAN, F., WANG, J., DING, L., HU, Y., LI, W., YUAN, Z., GUO, Q., ZHU, C., YU, L., WANG, H., ZHAO, Z., JIA, L., LI, J., YU, Y., ZHANG, W., CHU, G., CHEN, S., LI, B.: Tissue Engineering and Regenerative Medicine: Achievements, Future, and Sustainability in Asia, *Frontiers in Bioengineering and Biotechnology*, Vol. 8, 83, pp. 1-35, 2020. https://doi.org/10.3389/fbioe.2020.00083

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Role of digital innovation and business transformation for sustainable to micro, small and medium scale enterprises in Tamil Nadu: an analytical study

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Abstract: Small and medium-sized enterprises (SMEs) account for approximately 90% of all businesses and nearly 50% of global employment, with a significant share of these jobs held by women. Therefore, evaluating SME performance in business innovation and examining frameworks that integrate sustainability is crucial for addressing poverty and gender inequality in line with international standards. This study focuses on the role of digital innovation and technology transfer in fostering sustainability within the SME sector in Tamil Nadu. SMEs in this region face numerous challenges while simultaneously encountering new opportunities arising from digital transformation. Existing research highlights how digital technologies can enhance operational efficiency, reduce environmental impact, and promote social equity. By analysing relevant literature, conducting surveys, and interviewing key stakeholders, this research examines the current status of digital innovation and technology transfer among SMEs in Tamil Nadu and assesses their implications for sustainable development.

1 Introduction

Digital Transformation (DT) is increasingly redefining boundaries between organizations and industries, creating significant competitiveness challenges for enterprises. Beyond the GDP growth of India in the SMEs sectors also impacts the social and environmental aspects of sustainability. Further SMEs engaged in international trade tend to be more optimistic about the business landscape and exhibit positive job creation prospects. An analysis of 438 Italian SMEs also shows that DT positively affects their international performance. However, there is a notable tension between DT and environmental sustainability, as they often represent competing growth paths [1,2]. Digital Transformation is reshaping industries globally, and SMEs are no exception, and MSMEs in Tamil Nadu.

Objectives of the study

- To observe the current scenario of Business Innovation in the field of Digital transformation in SMEs in Tamil Nadu.
- To identify the challenges of business innovation and major factors of digital Transformation in SMEs sectors in Tamil Nadu.
- To find out the sustainability performance of SMEs.
- To propose a framework for leveraging DT for sustainable practices in SMEs.

Importance of the study

Informing Policy and Support Frameworks: The observation of the present research will useful to policymakers and support organizations in developing targeted programs and policies that facilitate Digital Transformation among SMEs. By identifying barriers and drivers of DT, the research can guide the allocation of resources and support mechanisms to help SMEs thrive.

Building Knowledge and Skills: This study addresses the knowledge gaps related to DT and sustainability in SMEs [3-5]. By providing a comprehensive analysis, it can serve as a valuable resource for training programs, workshops, and educational initiatives aimed at enhancing the digital skills and capabilities of SME owners and employees.

Regional Development Insights: By focusing on specific districts in Tamil Nadu, the study offers insights into regional variations in SME practices and challenges. This localized approach can help tailor interventions and support strategies to meet the unique needs of SMEs in different areas. Encouraging Collaboration: The study encourages collaboration among stakeholders, including government agencies, industry associations, and technology providers. By fostering partnerships, the research can enhance the collective effort for further research.

2 Research methodology

Sample Size: The 200 SMEs was targeted for this present study, distributed among the four districts as follows: Coimbatore District: 50 SMEs, Tiruppur District: 50 SMEs, Karur District: 50 SMEs, Erode District: 50 SMEs. The stratified random sampling technique was adopted.

Short comings of the study

The unique characteristics of the local market may not reflect broader trends. While the study aims to include 200 SMEs, this sample size may still be insufficient to capture the diversity of experiences and practices across all sectors and sizes of SMEs, potentially leading to biased conclusions. The study may prioritize quantitative metrics for assessing Digital Transformation and sustainability, potentially overlooking in observing the intangible services of SMEs sectors.

3 Results and discussion

Age Distribution: In the present study reveals that a significant portion of respondents fall within the age range of 46-50 years, accounting for 38% of the sample. Additionally, 22% of respondents are over 50 years old. This suggests that the workforce in the surveyed small and medium enterprises (SMEs) is predominantly mature, indicating potential stability and experience within the sector (Table 1).

Locality of SME Organizations: Geographic representation among the SMEs shows a noteworthy concentration in Tiruppur district, which comprises 37% of the respondents. This is followed by Coimbatore at 19% and Karur at 23%. The data highlights Tiruppur as a key area for SME activity, reflecting regional economic dynamics (Table 1).

Gender Distribution: Gender analysis demonstrates a significant disparity, with male respondents making up 71% of the sample while female respondents represent only 29%. This indicates a gender imbalance within the surveyed workforce, warranting further investigation into the factors influencing these demographics (Table 1).

Educational Qualification: The educational backgrounds of respondents vary considerably. School-level education constitutes 33% of the group, graduates account for 30%, and postgraduates represent 18%. This distribution suggests a diverse skill set, although a notable percentage lacks higher qualifications (Table 1).

Experience in the Field: A substantial majority of respondents (35%) have 10-15 years of experience in their respective fields. This finding underscores the presence of a relatively experienced workforce within the SME sector, likely contributing to overall industry stability (Table 1).

Type of Industry: The analysis identifies the food processing industry as the most prominent sector, representing 22% of the respondents, closely followed by leather manufacturing at 19%. These sectors highlight key areas of economic activity and employment in the region (Table 1).

Digital Transformation Adoption: The study indicates that a significant portion of SMEs falls into the "Partially Adoption" stage of digital transformation, with 41% of respondents in this category (Table 1).

Digital Tools Used: Among the digital tools utilized by SMEs, cloud services rank highest, with 38% of respondents employing them, followed by social media marketing at 21%. This reflects a growing recognition of the importance of digital solutions, although adoption remains inconsistent across the sector (Table 1).

Importance of Sustainability: Perspectives on sustainability vary among respondents, with 33% viewing it as less important and 22% considering it highly important. This disparity points to differing priorities within the industry regarding sustainable practices (Table 1).

Sustainability Practices: The study reveals that the most frequently implemented sustainability practice among respondents is sustainable sourcing, adopted by 40%. Community engagement follows at 27%, indicating awareness and initiatives aimed at improving local sustainability (Table 1).

Barriers to Digital Transformation: The primary barrier hindering digital transformation for the SMEs surveyed is resistance to change, reported by 40% of respondents. Additionally, a lack of skills is cited by 24% as a significant challenge, highlighting the need for targeted training and change management strategies (Table 1).

Table 1 Demographic details of the respondents and digital transformation adoption

I	DEMOGRAPHIC DETAILS OF THE RESPONDENTS	Number	%
1	Age of Respondent:		
	Below 30	42	21
	30-45	38	19
	46-50	76	38
	Above 50	44	22
		200	100
2	locality of the SME organization	42	21
	Coimbatore district	38	19
	Tiruppur district	74	37
	Karur district	46	23
	Erode district	200	100
3	Gender		
	Male	142	71
	Female	58	29
		200	100

4	Educational qualification	66	33
	School level	38	19
	Graduate	60	30
	Post graduate	36	18
	Others	200	100
5	Experience in the field of SME		
	less than 5 years	54	27
	5-10 years	36	18
	10-15 years	70	35
	More than 15 years	40	20
		200	100
6	Type of SME industry		
	Textile Manufacturing	36	18
	Leather Manufacturing	38	19
	Food process industry	44	22
	Electronic industry	30	15
	Engineering industry	20	10
	Coir industry	14	7
	Health care industry	18	9
		200	100
II	**DIGITAL TRANSFORMATION ADOPTION**		
1	How would you rate your company's current level of Digital Transformation? (1 = No Adoption, 4 = Full Adoption)		
	No adoption	35	17
	Semi Adoption	43	22
	Partially adoption	82	41
	Fully Adoption	40	20
		200	100
2	Which digital tools does your company currently use?		
	E-commerce platforms	42	21
	Social media marketing	41	21
	Cloud services	76	38
	Data analytics tools	41	20
		200	100
3	How important is sustainability to your business?		
	Highly important	44	22
	average important	54	27
	less important	66	33
	no important	36	18
		200	100
4	Which sustainability practices does your company implement?		
	Waste reduction	28	14
	Energy efficiency	38	19
	Sustainable sourcing	80	40
	Community engagement	54	27
		200	100
5	What barriers do you face in adopting Digital Transformation?		
	Lack of funding	32	16
	Lack of skills	48	24
	Resistance to change	80	40
	Technology limitations	40	20
		200	100

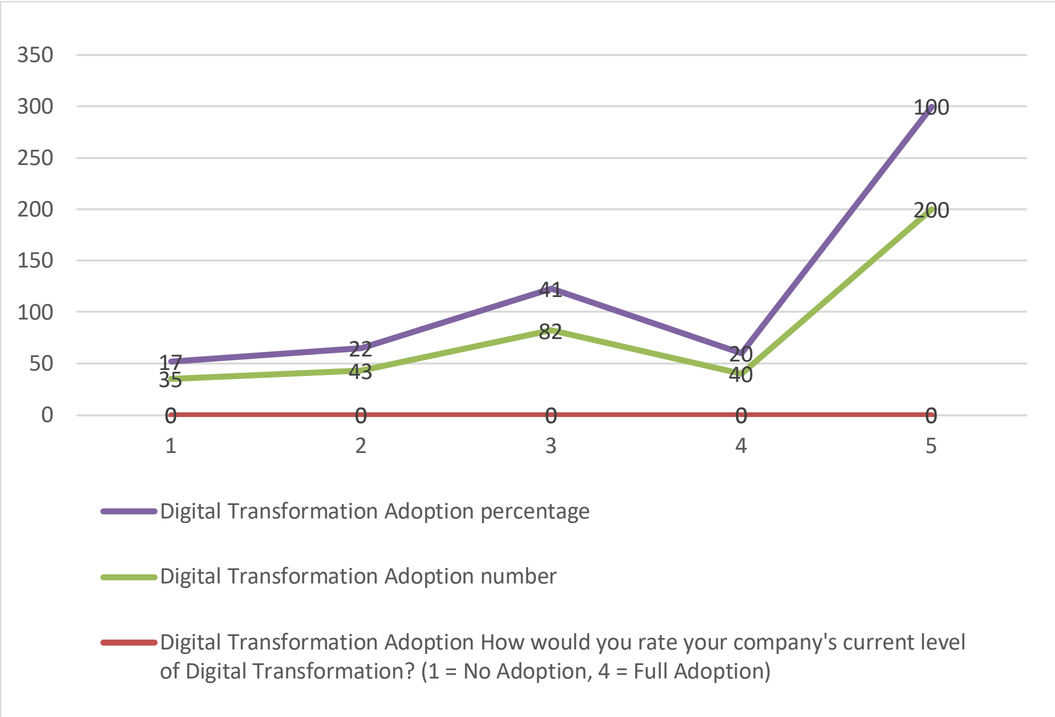

Figure 1 Current level of digital transformation in SME sector

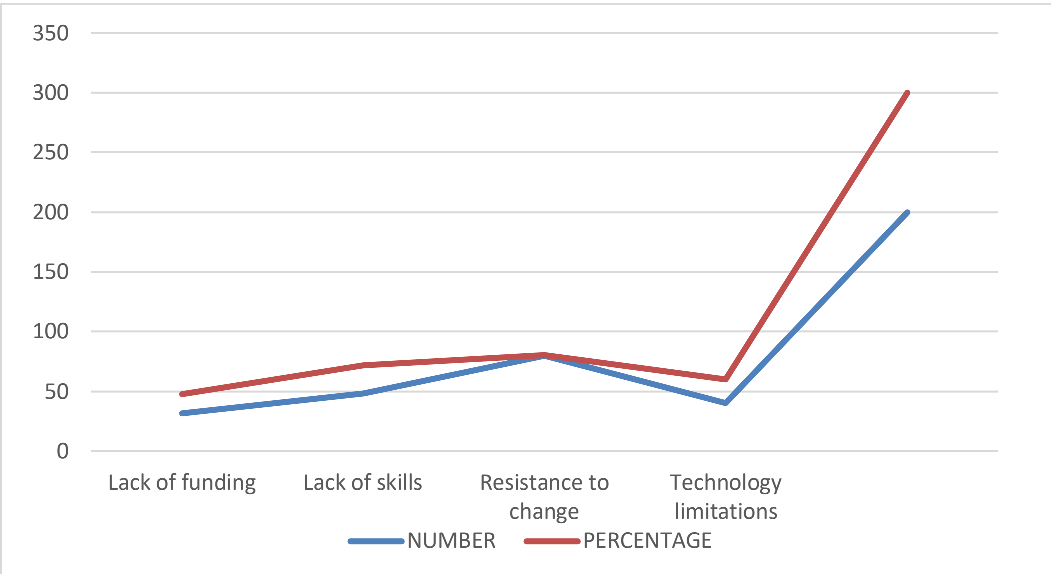

Figure 2 Challenges of adopting digital transformation

Increase Awareness and Training: To foster digital proficiency among SME workers, it is critical to organize workshops and training programs tailored to their specific needs. These initiatives should focus on topics such as building confidence in the use of digital tools. By offering hands-on training in cloud services, social media marketing, and data analytics, SMEs can empower their workforce to embrace digital transformation. This approach not only enhances skills but also mitigates anxiety related to new technologies, ultimately driving greater adoption and innovation.

Promote Gender Inclusivity: Addressing the gender imbalance in the workforce is imperative. Implementing gender-sensitive recruitment policies can help attract more female candidates, while fostering a supportive work environment will encourage retention and growth. Organizations should consider establishing mentorship programs and flexible working arrangements to support

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women in balancing work and personal commitments. By promoting female participation, SMEs can benefit from diverse perspectives, leading to improved innovation.

The business innovation programs could include subsidies or grants for investing in cloud services, data analytics, and other essential digital infrastructure. Enhanced financial support would lessen the burden of initial costs and encourage SMEs to integrate advanced technologies into their operations, ultimately driving efficiency and competitiveness in the market. Strengthen Sustainability Practices: Promoting sustainability within SMEs is not only essential for environmental responsibility but also crucial for long-term business viability. Initiatives aimed at raising awareness about the benefits of sustainable practices can include workshops, informational campaigns, and success stories from peers in the industry.

Establishing partnerships for training programs, internships, and research initiatives can create a pipeline of skilled talent equipped to navigate the digital landscape. Furthermore, local institutions can provide SMEs with valuable insights into current technological trends, allowing for more tailored and effective adoption of digital practices (Figure 1).

Current Scenario Elaboration: In light of these recommendations, the current scenario presents both challenges and opportunities for SMEs (Figure 2). The mature workforce, while experienced, may require reskilling to keep pace with technological advancements. The significant gender gap calls for proactive measures to ensure a more diverse and inclusive workforce, which can enhance creativity and problem-solving within organizations.

Digital tools like cloud services are underutilized, highlighting the potential for growth through increased investment and training. Moreover, the hesitance toward sustainability among some SMEs poses a risk, as businesses increasingly face pressure from consumers and regulatory bodies to demonstrate social responsibility. By executing these recommendations, SMEs can position themselves not only for immediate success but also for long-term sustainability,

4 Conclusion

The present data reveals that while many SMEs in Tamil Nadu recognize the importance of digital transformation, there is considerable room for improvement in adoption levels and sustainability practices. The findings highlight significant barriers, particularly resistance to change and a lack of skills, which must be addressed to foster a more digitally adept and sustainable SME sector. By implementing the recommended strategies, stakeholders may improve the capacity and ultimately contributing to the development and sustainability goals. The analysis of the demographic profile of SME respondents reveals a diverse range of ages, educational backgrounds, and experiences, which may influence their perspectives and approaches. It is a clear about importance of awareness in digital transformation and sustainability, significant barriers remain [6,7]. Addressing these challenges through strategic initiatives can empower SMEs to thrive in an increasingly digital and environmentally-conscious marketplace. Further, the study highlights the various component for achieving sustainable practices in SMEs. By overcoming existing barriers and fully embracing digital tools, SMEs can enhance their operational efficiency, contribute to sustainability goals in Tamil Nadu.

References

[1] IONASCU, A.E., BARBU, C.A., OLTEANU (BURCĀ), A.L.: *Sustainability in the Digital Age*, In: Chivu, L., Ioan-Franc, V., Georgescu, G., De Los Ríos Carmenado, I., Andrei, J.V. (eds) Europe in the New World Economy: Opportunities and Challenges. ESPERA 2023, Springer Proceedings in Business and Economics, Springer, Cham., pp. 513-524, 2024. https://doi.org/10.1007/978-3-031-71329-3_31

[2] BICAN, P.M., BREM, A.: Digital Business Model, Digital Transformation, Digital Entrepreneurship: Is There a Sustainable “Digital”?, *Sustainability*, Vol. 12, No. 13, pp. 1- 15, 5239, 2020. https://doi.org/10.3390/su12135239

[3] SOŁTYSIK, M., WOJNAROWSKA, M., URBANIEC, M., ZABKAR, V., ĆWIKLICKI, M., VARESE, E.: *Sustainable Business in the Era of Digital Transformation*, Strategic and Entrepreneurial Perspectives, Routledge, Abingdon, Oxon, New York, USA, 2024.

[4] GEORGE, G., SCHILLEBEECKX, S.J.D.: Digital transformation, sustainability, and purpose in the multinational enterprise, *Journal of World Business*, Vol. 57, No. 3, 101326, pp., 1-8, 2022. https://doi.org/10.1016/j.jwb.2022.101326

[5] BAPAT, V.: Sustainability: the next frontier of digital transformation, ERP Today, [Online], Available: https://erp.today/sustainability-the-next-frontier-of-digital-transformation/ [28 Oct 2025], 2022.

[6] VINARDI, C.: *Sustainable Performance in the Digital Age*, Springer Nature Switzerland, 2024. https://doi.org/10.1007/978-3-032-01252-4

[7] ORUGANTI, S.K., KARRAS, D., THAKUR, S., CHAITHANYA, J.K., METTA, S., LATHIGARA, A.: *Digital Transformation and Sustainability of Business*, CRC Press, 2025.

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