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Work, Success, and Career: Investigating the Academic Equivalent of a Triadic Relationship

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ABSTRACT Our research examines the impact of thriving at work on individual job performance through both direct effects and career satisfaction. The main purpose of our research is to empirically test the relationships between thriving at work, individual job performance and career satisfaction among higher education officials in Türkiye. The data of the research, which was conducted using the quantitative research model and correlational research design, were collected by convenience sampling method from 410 academicians working in the field of business administration at different universities in Türkiye. These data were analyzed using SPSS 25 and AMOS 25 statistical programs. Based on an extensive literature, we formulated two hypotheses that we tested in a single structural model using structural equation modeling (SEM) and the bootstrap technique. The findings demonstrated that there were positive and significant correlations between the variables of career satisfaction, individual job performance and thriving at work. Also, it was found that thriving at work had a mediating role in the effect of career satisfaction on individual job performance. With the understanding of the important effect of thriving at work in the relationship between career satisfaction and individual job performance, it is important to keep career satisfaction at a positive level since academics are expected to be more productive for development. In this context, academics should be encouraged to feel willing to work, energetic and open to self-improvement at work by making their career satisfaction positive.

KEYWORDS
Career satisfaction
Individual job performance
Thriving at work
Academicians
SEM
Mediation effect analysis
Bootstrap

INTRODUCTION

Human development and thriving at work has been one of the main areas of social sciences for a period of time (Kleine *et al.* 2019). One of the leading role players who will contribute to the development of human and society is academics. Academics are expected to be qualified in universities located at the centre of higher education (Žnidaršič and Marič 2021). In this respect, it is important to understand the determinants of academic success and performance in higher education institutions (Schneider and Preckel 2017). Career satisfaction, as a concept related to people's internal states (Greenhaus *et al.* 1990), is also discussed in this context. Career satisfaction is considered an indicator of the happiness that employees feel regarding how they manage their careers (Strauss *et al.* 2012) and is seen as one of the determinants of individual job performance (Garandai 2021; Motowildo *et al.* 1997).

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Career satisfaction, which highlights the individual and considers that the individual's internal standards are formed through the perception of satisfaction as a function of their success in the social environment, reveals the individual's work satisfaction and level of happiness (Ballout 2007). This affects the individual's life quality (Aytekin *et al.* 2016) and individual job performance. Indeed, individuals focus on improving themselves at work while aiming for a successful business life by improving their quality of life. Therefore, the relationship between career satisfaction and individual job performance makes the development and thriving at work of the employee even more attractive.

The concept of thriving at work is a growing concept that has attracted considerable attention in organizational studies (Paterson *et al.* 2014; Spreitzer *et al.* 2012) and that has received great attention in the field of organizational behavior as a component of long-term performance (Abid *et al.* 2019). Despite the fact that research on thriving at work has increased in the recent years, this literature is still scattered and necessitates systematic and theory-based syntheses (Kleine *et al.* 2019). Researchers have noted that thriving at work is associated with various important organizational outcomes such as job satisfaction, personal development, orga-

nizational commitment, organizational citizenship behavior, and performance. Abid *et al.* (2019) suggested in their meta-analysis that most research on thriving at work has been conducted in developed countries such as the United States, China, Australia, Belgium, and France.

In line with the explanations above, this study was conducted to examine the relationships between career satisfaction, individual job performance, and thriving at work. This purpose was addressed by answering the following question: What is the relationship between career satisfaction and individual job performance, and what is the role of thriving at work among academic staff in Türkiye on their performance in this relationship? In this context, while the relationship between career satisfaction and individual job performance was examined in the first stage, the mediating role of thriving at work in this relationship was determined in the second stage. As a result of the literature review, no study was found that addresses these three variables together. In this regard, it can be said that the present study represents an early and original contribution examining the relationship between these three variables in the context of higher education.

This research provides a novel contribution to the academic literature in three principal domains. Initially, a survey of the current literature indicated that no research has been identified that concurrently investigates the factors of career satisfaction, individual work performance, and thriving at work. This research represents a pioneering study that examines the relationships between these three critical concepts within the context of higher education, thereby filling a gap in the literature. Secondly, the study's most original theoretical contribution lies in its empirical testing of the mediating role of thriving at work in the effect of career satisfaction on individual job performance. This explains how career satisfaction influences performance not only directly but also indirectly, through the individual's sense of vitality and openness to learning that is, through professional development in the workplace. Finally, given that the vast majority of research on thriving at work has been conducted in developed countries such as the United States, China, Australia, Belgium and France (Abid *et al.* 2019), this study advances the literature within the context of a developing country and specifically regarding academic performance by taking academics working in higher education institutions in Türkiye as its sample.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Career satisfaction

The career phenomenon, which involves the idea of progressing with people's feelings and thoughts, knowledge and abilities, is a lifelong process (Spurk *et al.* 2015). In this process, many career-related concepts (like career planning, career determination & indecisiveness, career dedication, career awareness, career anxiety and career stress) have emerged. One of the concepts mentioned is "career satisfaction", and it has taken its place among the organizational and administrative issues that have been studied intensively in the recent years (Ding *et al.* 2023; Latan *et al.* 2022; Park 2018). Career satisfaction, defined as the positive psychological outcomes or gains that an individual accumulates as a result of work experiences (Judge *et al.* 1995), is considered as a dynamic structure that reflects how the individual feels about their job and career (Durmuş and Akyüz 2021). In this regard, career satisfaction is used to measure how consistent individuals' career improvement is with their own goals, values and preferences, and to evaluate their career positioning.

According to Chang *et al.* (2020), career satisfaction is evaluated both objectively and subjectively. Objective indicators like job title, salary, and number of promotions in a year can be observed directly. Therefore, they can be evaluated by others. However, subjective career success is an individual's feeling of accomplishment and satisfaction with their career achievement. Although the first studies on career satisfaction focused on the objective aspect of the concept, it has been determined that individuals who have made a certain progress in their professional careers over time and who have reached the desired status and income have become alienated from their careers both individually and socially (Shockley *et al.* 2016). Thus, the focus of career satisfaction has moved away from objective criteria towards subjective perceptions. Today, career satisfaction is evaluated with both objective and subjective aspects (Rençber and Paşaoğlu Baş 2021).

Career satisfaction is an antecedent of many individual and organizational variables such as subjective well-being (Nae and Choi 2022), organizational commitment (Baidoun and Anderson 2023), work engagement (Timms and Brough 2013), psychological empowerment (Sun *et al.* 2022), organizational citizenship behavior (Lv and Yu 2020), career commitment (Onyishi *et al.* 2019), work-life balance, proactive behavior (Palabıyık and Yücel 2018), happiness (Denizli and Dündar 2020), life satisfaction (Hagmaier *et al.* 2018), job satisfaction, and self efficacy (Honicke *et al.* 2023). Additionally, it has been proven that career satisfaction has positive effects in preventing or reducing negative behaviors such as burnout (Opoku and Apenteng 2014), intention to leave (Osei *et al.* 2023), career stress (Yang and Yang 2019), and job stress.

The relationship between career satisfaction and individual job performance

Individual job performance is the quantitative or qualitative or qualitative expression of the extent to which an individual achieves the goals and desired standards set for themselves within the scope of the goals of the institution. Motowidlo and Kell (2012) defined individual job performance as "the total expected value to the organization of the discrete behavioral episodes that an individual carries out over a specified period". Individual job performance is dealt with two dimensions as task performance and contextual performance (Borman and Motowidlo 1997). Task performance refers to the person's performance in the tasks that are included in the job description and that constitute the basic work of the organization (Koopmans *et al.* 2011).

The individual's abilities, professional knowledge, skills, and experience are the main determinants of task performance (Motowildo *et al.* 1997). In order to distinguish the work and activities within the scope of job performance from others, the work and activities performed must be those included in the official job descriptions (Rotundo and Sackett 2002). Contextual performance is important behaviors that are not directly related to the main task activities, but serve to create a clean atmosphere in the organizational, social, and psychological context for these tasks. Such behaviors include being volunteer to perform tasks that are not formally part of the job (Borman 2004). Contextual performance includes such activities as the good relationships that people establish with their colleagues, cooperation, or the extra efforts they make to complete work on time. With this regard, it creates the social and psychological basis necessary to achieve organizational goals (Motowildo *et al.* 1997). Therefore, since individual job performance includes actions that contribute to organizational performance, it is expressed as the sum of the activities that enable the organization to operate efficiently.

In addition, it should not be forgotten that individual job performance is important for the individual as well as for the organization. While individual high performance is a source of moral pride, happiness and satisfaction, it also means financial promotion, being indispensable for the institution, or recognition in the sector. Individual job performance attracts attention as an important dependent variable of human resources management, organizational psychology, and organizational behavior, and there are many studies present to determine the factors that reveal individual job performance. When the literature is examined, career satisfaction is considered as an antecedent of individual job performance. In other words, it is accepted that career satisfaction has a positive effect on individual job performance (Garandai 2021; Nisar and Rasheed 2020; Dubbelt *et al.* 2019; Trivellas *et al.* 2015; Karatepe 2012). Given the this statements, the following hypothesis is developed and tested in the present study. H1. Career satisfaction has a positive direct effect on individual job performance.

The mediating role of thriving at work

Thriving at work has earned its well-deserved place in positive organizational behavior, and many scholars have emphasized the importance of its outcomes in the last decade (Ni *et al.* 2023; Okros and Vîrgă 2022). It is defined as a psychological state in which individuals experience a sense of both vitality and learning at work (Spreitzer *et al.* 2005). The first component, vitality, refers to the individual's feeling of being energetic, excited and passionate at work. Learning, which is the other component, emphasizes the improvement of the individual at work with new knowledge and skills (Spreitzer *et al.* 2012). These two components of thriving at work usually function simultaneously (Karataş and Çankır 2023). For example, individuals may feel alive at work, with a sense of steady improvement without the learning process, and with the influence of co-workers and a cheerful work environment. However, if the individual experiences vitality at work without the desire to learn, or if the individual does not want to improve their skills or acquire new knowledge about their job, they will not be able to improve themselves at work. Similarly, if a person wants to improve their professional skills with a feeling of burnout, they will still not be able to improve themselves (Spreitzer *et al.* 2005).

Therefore, although a person who feels one of these emotions at work may make some progress and development, they must improve their feelings of vitality and learning in harmony so as to improve themselves at work accurately (Porath *et al.* 2012). Thriving at work can benefit both individuals and organizations. Thus, when studies have examined about the thriving, it has seen that many positive outcomes such as job satisfaction (Jiang *et al.* 2020), voice behavior (Sheng and Zhou 2021), work engagement (Zhai *et al.* 2022), organizational commitment (Walumbwa *et al.* 2018), life satisfaction (Zhai *et al.* 2020), employee health (Kleine *et al.* 2023), thriving at work (Paterson *et al.* 2014), happiness at work (Qaiser *et al.* 2018), creative performance (Kleine *et al.* 2019) and job performance (Elahi *et al.* 2020; Farid *et al.* 2023; Okros and Vîrgă 2022).

Thriving at work also reduces negative organizational outcomes such as burnout, depression, stress, poor job fit, absenteeism, turnover intention, detachment, bullying or other illnesses (Bolat *et al.* 2018; Forbes 2013). In addition, the results of many studies indicate that thriving at work is used as a mediator variable (Abid *et al.* 2018; Alwahhabi *et al.* 2023; Baş 2022; Xie *et al.* 2023; Yang *et al.* 2021; Zhai *et al.* 2020; Zhu *et al.* 2023) Thus, the following mediation hypothesis is proposed: H2: Thriving at work as mediation role between career satisfaction and individual job performance. Based on the above-mentioned studies, the theoretical assumptions and the hypotheses that were formed, career satisfaction was taken as the predictor variable, thriving at work as the mediating variable, and individual job performance as the dependent variable. The model that deals with these variables is presented in Figure 1.

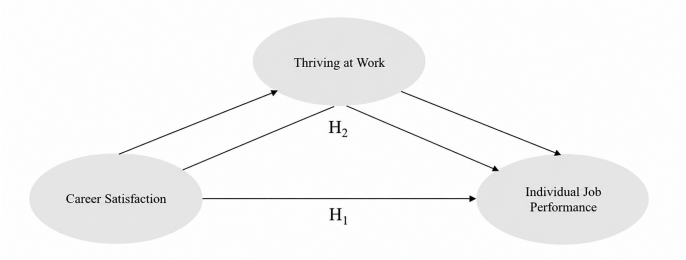

Figure 1 Hypothesized Research Model

METHODOLOGY

Sample and data collection

The intended audience for this study comprises scholars from business faculties at many state universities in Türkiye. The rationale for selecting academics can be explained as follows: The absence of studies examining the mediating effect of thriving at work on individual job performance, coupled with the necessity to more clearly observe and measure the relationship between career progression and individual development within an academic framework, substantiates the choice of this sample group. Furthermore, this situation is noteworthy in that it highlights how employees perform in their respective fields and how they interact with one another within the organisation (Altınsoy and Erdoğmuş 2023).

The study employed a convenience sampling method. The main reason for opting for this method is the lack of a comprehensive sampling framework that would enable us to reach all academics in business departments at state universities across Türkiye, as well as time and resource constraints. Whilst convenience sampling enhances the efficiency of the research process, it is acknowledged that it imposes certain limitations on the generalisability of the findings. The data was collected via a survey link shared via Google Forms between August and November 2023. The study was conducted with the approval of the Human Research Ethics Committee at KTO Karatay University, and the necessary permissions were obtained (decision no.: 2023/04/13, date: 28 April 2023). During the data analysis process, 18 questionnaires were excluded for various reasons, and the remaining 410 valid questionnaires were included in the analysis.

In multivariate studies, it is stipulated that the sample size should be 10 times or more than the number of variables in the research, and the sample size to be selected for the research should be at least 170 (Büyüköztürk 2012). Therefore, the required condition for the sample size was met in this study. The sample of 410 participants obtained in this study meets the relevant criterion. However, the fact that the sample comprises only academics from business departments at state universities limits the generalisability of the findings to other disciplines or private universities. An analysis of the demographic distribution of the sample reveals that participants were aged between 22 and 67, with the vast majority (39%) falling within the 36–45 age group. Of the participants, 210 (51.2%) were men, 214 (52.2%) were married and 157 (38.3%) were senior lecturers. In terms of professional experience, it was found

that the majority of participants (43.7%) had between 6 and 15 years' experience. It is considered that this demographic distribution largely corresponds to the general profile of academics in the business administration department in Türkiye. However, it is recommended that caution be exercised when generalising these findings to a wider population.

Measures

Each item in the scales was graded according to a five-point Likert scale ranging from "Strongly Disagree (1) to Strongly Agree (5)". Career satisfaction The Career Satisfaction scale was developed by Greenhaus *et al.* (1990), was first adapted into Turkish by Kaya (2018). The Career Satisfaction scale is a one-dimensional five-item scale. The scale, which does not have reverse coded items, includes statements such as "I am satisfied with the progress I have made toward meeting my overall career goals" and "I am satisfied with the progress I have made toward meeting my goals for thedevelopment of new skills". Confirmatory factor analysis (CFA) was performed on the scale and the fit index values of the scale (χ^2/df = 3.22; p <.001; GFI = .98; CFI = .99; RMSEA = .07; SRMR = .01) were found. Regarding reliability, the scale's coefficient of internal consistency was .87. (Kaya 2018). In this study, Cronbach's α coefficient was high (α = .945, CR = .79, AVE = .81).

Thriving at work The Thriving at Work scale was developed by Porath *et al.* (2012), was first adapted into Turkish by Koçak (2016). The scale has 8 items in 2 dimensions (vitality and learning). The Thriving at Work scale includes items such as, "At work, I have energy and spirit" and "At work, I have energy and spirit". The fit index values of the scale (χ^2/df = 3.64; p <.001; GFI = .96; CFI = .98; RMSEA = .08; SRMR = .07) were found. The adapted into Turkish scale exhibited a high composite reliability and validity (Composite Reliability (CR): .86; Average Variance Extracted (AVE): .75). In the present study, the scale reliability coefficients reached a good level (α = .98, CR = .79, AVE = .81).

Individual job performance The Individual Job Performance scale was developed by Kirkman and Rosen (1999) and later used by Sigler and Pearson (2000). The scale, which was adapted into Turkish by Çöl (2008), is a one-dimensional four-item scale. The Individual Job Performance scale includes items such as, "I complete my tasks on time'" and "I make sure that products meet or exceed quality standards". The fit index values of the scale (χ2/df = 3.08; p <.001; GFI = .92; CFI = .93; RMSEA = .04; SRMR = .02) were found. Regarding reliability, the scale's coefficient of internal consistency was .83. (Çöl 2008). In this study, the scale's reliability coefficients were high (α = .98, CR = .85, AVE = .80).

Data analysis

IBM Statistical Package for Social Sciences (SPSS 25) and Analysis of Moment Structures (AMOS 23) programs were used to analyze the data obtained in the research. The descriptive statistics, assumptions of normality and reliability coefficients were examined. The associations between the variables were analyzed using correlation analysis. Utilizing the bootstrap method, an analysis was conducted to ascertain whether thriving at work mediates the relationship between career satisfaction and individual job performance. In the analysis, 5000 resampling alternatives were preferred using the bootstrap technique and to validate the research hypothesis, efforts were made to confirm that the 95% confidence interval (CI) values derived from the analysis did not encompass zero (0) values (Hayes 2018).

RESULTS

Preliminary analysis

The means, standard deviations, skewness and kurtosis coefficients, and correlations are shown in Table 1.

Table 1 Descriptive statistics and Correlations

	$\bar{x}$	s.d.	Skewness	Kurtosis	1	2	3
1. Career Satisfaction	3.31	1.25	-.45	-1.28	1		
2. Thriving at Work	3.29	1.11	-.46	-1.39	.71**	1	
3. Individual Job Performance	3.69	1.14	-.94	-0.52	.79**	.76**	1

Note: ** There is a significant relationship at the level of p < 0.01

When Table 1 is examined, it is seen that the skewness and kurtosis coefficients of the scales meet the condition of ±1.5 range. The fact that the coefficients in question are within this range shows that the data exhibit a normal distribution (Tabachnick *et al.* 2013). The correlation analysis indicated that career satisfaction was positively and significantly related to both thriving at work (r = –.71, p < .01) and individual job performance (r = –.79, p < .01). Finally, results showed that thriving at work was significantly related to individual job performance (r = .76, p < .01).

Structural equation model

Before testing the hypotheses proposed within the scope of the research model, CFA was conducted to determine the structural validity of the scales used in the research. During the analysis, care was taken to ensure that the standardized regression coefficient of the items in the scale should not be lower than 0.70 and the p value should not be higher than .05 (Hair et al., 2009, p. 679). Table 2 shows the fit index values obtained after modification.

Table 2 Criteria for Goodness of Fit Values

Model	p	α	CMIN/DF2<x2/df<5	GFI>.90	CFI>.90	RMSEA<.08	SRMR<.08
Model of Measurement	.00	.98	3.19	.89	.97	.07	.02

When Table 2 is examined, it is seen that the fit indices of the scales are in the range of the fit index values taken as reference (Thakkar, 2020).

Mediation analysis

In this study, we examined the mediating effects of thriving at work on the reltionship between career satisfaction and individual job performance. The results of the analysis are shown in Table 3.

IMPLICATIONS

Theoretical implications

The current research is a study designed to understand the impact of career satisfaction on job performance. The research contributes to the existing literature as it is one of the pioneer studies to investigate the indirect effect of career satisfaction on individual job performance through thriving at work. According to the results of the analysis, it was revealed that the hypotheses supported the model. First of all, the positive relationship between career satisfaction and individual job performance was empirically confirmed in the study.

Table 3 Results of Standardized Coefficients for the Hypothesized Model

Prediction Variables	Outcome Variables			
	Thriving at Work		Individual Job Performance	
	β	SE	β	SE
H_1 (Career Satisfaction → Individual Job Performance)	–	–	0.62***	0.044
R^2	–	–	0.66	
Career Satisfaction → Thriving at Work	0.81***	0.046	–	–
R^2	0.65***		–	
Thriving at Work → Individual Job Performance	–	–	0.24***	
R^2	–	–	0.68	0.052
H_2 (Career Satisfaction → Thriving at Work → Individual Job Performance)	–			
Career Satisfaction → Individual Job Performance	–		0.19***	0.052
Thriving at Work → Individual Job Performance	–		0.61***	0.063
R^2	–		0.68	
Indirect Effect				
Career Satisfaction → Thriving at Work → Individual Job Performance	–		0.19, (0.061–0.321)	

Note: (*p < .01, ***p < .001).

The findings mentioned above provided evidence that career satisfaction was an antecedent of individual job performance, which was suggested by various researchers. These findings are in line with the findings of the study conducted by Aytekin *et al.* (2016) that the scientific performance of the academic staff who invested in their careers and who were highly motivated would be higher. Previous studies on career satisfaction revealed that career satisfaction had correlations with important concepts related to many of the theory's job outcomes like performance.

Dubbelt *et al.* (2019) examined that job commitment, talent, and performance were related to career satisfaction. Greenhaus *et al.* (1990) argued that improving the career satisfaction of employees within organizations reduced the negative impact of stress caused by their jobs and thus increased the individual job performance of employees. The theoretical mechanism underlying these relationships can be explained through multiple complementary frameworks discussed in this study. From a Conservation of Resources (COR) perspective, career satisfaction functions as a personal resource that energizes individuals and fosters thriving at work, which in turn enhances individual job performance. Self-Determination Theory further supports this mechanism by suggesting that when individuals experience satisfaction in their careers, their fundamental needs for autonomy and competence are fulfilled, thereby cultivating a sense of vitality and a willingness to learn the two core dimensions of thriving at work. Additionally, consistent with Social Exchange Theory, academicians who perceive their career progress as rewarding are more likely to reciprocate through heightened engagement and superior job performance. Together, these theoretical perspectives provide a coherent explanation for why thriving at work serves as a meaningful mediator between career satisfaction and individual job performance.

Secondly, light is shed on the individual and organizational behavioral antecedents of thriving at work. Thriving at work provides an important self-improvement structure for the individual and plays an important role in fulfilling their duties and responsibilities at the workplace (Elahi *et al.* 2020). Previous studies revealed that it promoted the individual success of employees and positively affected individual job performance (Elahi *et al.* 2020; Abid *et al.* 2018; Prem *et al.* 2017; Paterson *et al.* 2014; Porath *et al.* 2012; Spreitzer *et al.* 2012). From an organizational perspective, it was observed that it affected employees in terms of their organizational trust levels, commitments, and organizational citizenship behaviors (Xie *et al.* 2023; Baş 2022; Zhai *et al.* 2022; Walumbwa *et al.* 2018; Carmeli and Spreitzer 2009). The studies mentioned above confirmed that individuals tended to exhibit better individual job performance when they felt alive and were eager to work (Spreitzer *et al.* 2005). For this reason, this study contributed to the literature by examining thriving at work as a mediating variable that could explain the impact of career satisfaction on individual job performance.

Practical implications

This study offers important implications for administrators, practitioners, and academic staff. First of all, it was determined in the study that career satisfaction was an important determinant of thriving at work and individual job performance. Considering the fact that the studies and research carried out by academic staff as a result of their performance are effective in shaping the careers of individuals who will form the future of other sectors (Baruch and Hall 2004, p. 9)(Dominic *et al.* 2021), their career satisfaction should be kept at a positive level as the academic staff are expected to be more productive towards improvement by governments, institutions, organizations, and universities (De Janasz and Sullivan 2004).

Besides, the study explained the importance of examining the indirect effect of thriving at work on the correlation between career satisfaction and individual job performance. The setting and incentives for individuals to improve themselves at work bring together positive results (Paterson *et al.* 2014). Individuals who feel that they can improve themselves at work exhibit better individual job performance (Spreitzer *et al.* 2005). They become more creative, productive, adaptable and satisfied with their jobs (Paterson *et al.* 2014) In the light of this information, considering that the contribution to knowledge through academic publications, lecturing, and producing projects has a great impact on professional reputation and career advancement (Altınsoy & Erdoğmuş, 2019), academic staff should be encouraged to become open to thriving at work, be willing to work, and feel energetic by making their career satisfaction positive.

From the perspective of university administrators and policymakers, these findings underscore the importance of developing institutional policies aimed at enhancing academic staff's career satisfaction. In this regard, measures such as making academic promotion criteria more transparent, expanding mentoring programs, and increasing research funding can have a positive impact on career satisfaction. In addition, fostering a workplace culture that supports thriving at work by providing autonomy, collaboration, and opportunities for continuous learning, can directly and indirectly enhance the individual job performance of academic staff. In the context of higher education policy in Türkiye, structural reforms implemented by relevant institutions, particularly the Council of Higher Education (YÖK) to improve the professional development environment for academics are likely to foster a more motivated, high-performing academic workforce, ultimately contributing to the broader goals of research productivity and educational quality in Turkish higher education.

CONCLUSION

Our study has some limitations that will guide future research. First, the direct effect of career satisfaction on individual job performance and the mediating effect of thriving at work in this relationship were examined by using a cross-sectional study design. In future studies, longitudinal and experimental designs can be used

to determine the causality between variables. Secondly, the data were obtained only from some public universities and business administration departments in Türkiye. Therefore, it is not possible to generalize the findings. Considering the differences in national and institutional culture, future studies can be planned and tested in different countries so that the findings can be generalized. Apart from public universities, the issue can also be examined in private universities established in Türkiye within the scope of Article 130 of the Turkish Constitution, provided that they are not aimed at making profit, or in private universities functioning around the world. In addition to all these, different findings can be revealed through different studies by not restricting the sample to academic staff only in the studies to be carried out, and thus research results can be improved. In addition, the data in this study were collected using a survey method based on the self-assessments of academic staff. The fact that all variables are reported by the same participants at the same time carries the risk of common method bias (Podsakoff et al., 2003). Recognizing this limitation, a multi-source approach is recommended for the future.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Piezoelectric Energy Harvesting in Urban Infrastructure: Electrical Power Generation from Pedestrian and Traffic-Induced Mechanical Vibrations

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ABSTRACT Increasing population, transportation density, and the growing demand for sustainable energy have intensified interest in alternative energy-generation technologies, particularly within urban infrastructure. Among these technologies, piezoelectric energy harvesting has emerged as a promising approach for converting mechanical energy generated on large urban surfaces, such as road pavements and sidewalks, into electrical energy. Various roadway- and pedestrian-based piezoelectric energy harvesting systems, including cantilever structures, deformable beams, multi-sensor mats, and hybrid triboelectric–piezoelectric designs, have demonstrated the capability to generate usable electrical power under realistic traffic and pedestrian loading conditions while requiring minimal infrastructure modification. These advances highlight the significant potential of piezoelectric sidewalks as sustainable and self-powered energy sources for future smart city applications. In this paper, roadway and sidewalk-based piezoelectric energy harvesting technologies reported in the literature are comprehensively reviewed, with particular emphasis on pedestrian-driven piezoelectric sidewalks and their implementation in everyday urban environments. Material selection, mechanical design, electrical interfacing, and potential application areas are examined from a holistic perspective. By synthesizing recent advances and identifying current challenges and future research directions, this review provides a comprehensive framework for the development of sustainable, low-power, and low-maintenance piezoelectric infrastructure systems suitable for next-generation smart cities.

KEYWORDS
Piezoelectric energy harvesting
Smart city infrastructure
Pedestrian-induced
Power generation

INTRODUCTION

During the construction and operation of roadway transportation systems, a substantial amount of energy is released in the form of heat, vibration, and deformation, much of which is dissipated into the environment (Gammaitoni 2012; Moure *et al.* 2016). In line with the objective of developing sustainable and "green" transportation infrastructure, energy harvesting (EH) from road surfaces aimed at recovering this wasted energy has become an important research field in recent years (Gholikhani *et al.* 2020; Ting *et al.* 2012; Pan *et al.* 2019). Road pavements and sidewalks simultaneously host multiple renewable energy sources due to their large surface areas, high thermal gradients, solar radiation, wind corridors, and mechanical energy generated by vehicle and pedestrian loads (Gammaitoni 2012; Jung *et al.* 2017). In this context, photovoltaic panels, thermoelectric generators, electromagnetic generators, and piezoelectric systems are the primary technologies proposed for pavement-based energy generation (Gammaitoni 2012; Song *et al.* 2019; Wang *et al.* 2020; Pirisi *et al.* 2013).

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Thermal- and solar-based systems utilize temperature differences between pavement layers through embedded fluid channels or thermoelectric modules, while photovoltaic roadway panels generate electricity directly from solar radiation (Moure *et al.* 2016; Jung *et al.* 2017; Gholikhani *et al.* 2019). However, issues such as high installation costs, rapid mechanical degradation under heavy traffic, and lower-than-expected electrical output limit the widespread adoption of these solutions (Gholikhani *et al.* 2019; Wang *et al.* 2016). Electromagnetic generators that harness mechanical energy, although capable of producing relatively high power output, are constrained, particularly on high-speed roadways by their requirement for large displacements, bulky mechanical components, and the formation of perceptible surface deflections, which adversely affect user comfort (Ting *et al.* 2012; Liu *et al.* 2018; Ambrozkiewicz *et al.* 2021). For these reasons, piezoelectric energy harvesting (PEH) has emerged as a more suitable alternative compared to other methods, particularly for applications involving small displacements and low-power loads (Gholikhani *et al.* 2020; Qin *et al.* 2022; Duc *et al.* 2022; Thai *et al.* 2021). Piezoelectric materials are capable of directly converting stresses and deformations induced by vehicle loads on road pavements and by pedestrian footsteps on sidewalks into electrical potential (Gammaitoni 2012; Tho *et al.* 2021).

Numerous roadway and sidewalk applications employing PZT (lead zircon ate titanate)-based disks, columns, stacks (piles), cym-

bal transducers, beams, cantilevers, and fixed–fixed beam geometries have been reported in the literature (Duc *et al.* 2022; Song *et al.* 2016; Hong *et al.* 2021; Wen *et al.* 2018; Yang *et al.* 2019). However, due to the brittle and fatigue-sensitive nature of PZT materials, direct exposure to wheel loads can lead to cracking and depolarization, resulting in performance degradation (Ahn *et al.* 2018; Daqaq *et al.* 2014). Consequently, cantilever array systems that isolate transducers from direct compressive loads and utilize traffic-induced free vibrations (Gammaitoni 2012; Wu *et al.* 2018), as well as beam-based configurations operating under axial deformation at small displacement levels, have been proposed as alternative solutions (Moure *et al.* 2016; Hu and Xu 2014).

Recent studies have compared the voltage and power levels obtainable from low-cost PZT modules embedded in different pavement structures including granular, asphalt, and concrete layers and have demonstrated that embedded modules can achieve higher efficiency, particularly in flexible pavements (Papagiannakis *et al.* 2017). Comprehensive review studies on roadway energy harvesting technologies have evaluated photovoltaic, thermoelectric, electromagnetic, and piezoelectric approaches in terms of energy conversion efficiency, continuity, storage capability, and cost, emphasizing that piezoelectric systems are especially well suited for low-power wireless sensors, monitoring systems, and signaling devices (Ting *et al.* 2012; Wang *et al.* 2016; Jaffe *et al.* 1955). Similarly, preliminary experiments conducted with various types of piezoelectric sensors embedded in asphalt pavements have revealed that the resulting voltage levels are promising for future LED road markers and small electronic components (Kawai 1969).

Piezoelectric energy harvesting holds significant potential not only in vehicular traffic applications but also through pedestrian-induced kinetic energy in everyday environments. Numerous studies have investigated floor tiles, multi-sensor foot-mat systems, stair steps, and public-area flooring designed to harvest energy from human footsteps (Ke and Wang 2012; Solyaev *et al.* 2020; Wang *et al.* 2018; Xiang *et al.* 2020). In locations with high pedestrian density such as mosques, metro entrances, shopping malls, and stadiums, piezoelectric–triboelectric hybrid systems have been reported to offer higher efficiency and improved scalability compared to standalone piezoelectric solutions (Sharuddin *et al.* 2020). In these applications, system performance is governed not only by mechanical design but also by the rectification stage, power management circuits, and the selection of appropriate energy storage or super capacitor systems (Solyaev *et al.* 2020).

The existing literature indicates that energy harvesting from both road pavements and sidewalks is technically feasible and may be economically viable for specific applications; however, numerous unresolved issues remain regarding conversion efficiency, material durability, fatigue behavior, embedding depth, user comfort, and long-term reliability Ting *et al.* (2012); Ahn *et al.* (2018); Daqaq *et al.* (2014); Jaffe *et al.* (1955). Consequently, recent studies have focused not only on the development of novel piezoelectric materials and structural configurations, but also on evaluating the performance and durability of prototypes operating under real-field conditions Gammaitoni (2012); Moure *et al.* (2016); Wu *et al.* (2018); Papagiannakis *et al.* (2017).

In this paper, based on roadway and sidewalk-based piezoelectric energy harvesting studies reported in the literature, particular emphasis is placed on piezoelectric sidewalks and pedestrian-based piezoelectric energy harvesting in everyday environments. Material selection, mechanical design, electrical interfacing, and potential application areas are discussed from a holistic perspective. Accordingly, this study aims to provide a framework for the development of sustainable, low-power, and low-maintenance piezoelectric infrastructure systems suitable for smart city applications.

The main contributions of this study include the experimental quantification of pedestrian-induced piezoelectric energy harvesting performance under controlled laboratory conditions through the measurement of peak voltage, current, and energy generated per step. In addition, a two-loop cascade control (TLCC)-based DC–DC regulation strategy is integrated and experimentally validated to maintain a stable 5 V output under dynamically varying input voltages. Furthermore, the effects of different embedding depths, sensor configurations, and loading scenarios are comparatively evaluated to assess both the structural integrity and electrical performance of piezoelectric systems in pedestrian and vehicular environments. Collectively, these contributions help bridge the gap between laboratory-scale piezoelectric prototypes and scalable smart infrastructure applications.

MATERIALS AND METHODS

This study is based on a comprehensive research framework that evaluates the piezoelectric energy conversion mechanism through both laboratory-scale experiments and real-field testing. All methodologies were designed as a multi-component methodological framework, taking into account current trends in the literature on sustainable roadway infrastructure, renewable energy technologies, and intelligent transportation systems (Gammaitoni 2012; Moure *et al.* 2016). Within this framework, various sensor types, embedding depths, loading scenarios, and electrical power regulation systems were employed, and each subsystem was systematically evaluated in terms of performance, durability, and energy generation capability.

Table 1 Material Properties of the Piezoelectric Sensors

Property	Sensor Type A (PZT-5H)	Sensor Type B (PVDF)
Material	Ceramic (PZT)	Polymer (PVDF)
Diaphragm Diameter	20 mm	15 mm
Piezoelectric Coefficient (d_{33})	560 pC/N	28 pC/N
Capacitance	24 nF	4.7 nF
Metal Plate Material	Brass	Aluminum
Total Thickness (Piezo + Metal)	0.62 mm	0.45 mm
Maximum Output Voltage (Open Circuit)	33.7 V	12.4 V
Application Area	Sidewalk / Vehicle Load	Pedestrian Energy Harvesting

Piezoelectric Materials and Components

Aggregate and Bitumen: The aggregates used in the experimental asphalt specimens were supplied by KOLSAN Inc., located in Afyonkarahisar, and were separated into three particle size fractions: 0–4 mm, 4–11 mm, and 11–22 mm. The aggregates were washed, sieved, and dried at 120 °C in accordance with the Turkish Highway Technical Specifications (HTS). Mechanical properties of the aggregates such as Los Angeles abrasion resistance, specific gravity, water absorption ratio, and resistance to fragmentation were determined under laboratory conditions, and the corresponding values are presented in Table 2. B 50/70 penetration-grade bitumen produced at the Aliağa Refinery was used as the binder. The softening point, penetration value, viscosity, flash point, and aging resistance of the bitumen were tested in accordance with relevant standards (Gholikhani *et al.* 2020). These asphalt components were selected to provide an optimal balance between stiffness and flexibility, ensuring both structural integrity and mechanical protection

of the embedded piezoelectric units under operational conditions (Ting *et al.* 2012).

Piezoelectric Sensors: Multiple types of piezoelectric sensors were employed in the experiments. The selection of these sensors was designed in a multi-layered manner to enable a comparative evaluation of the energy generation characteristics under different loading conditions, including single impacts, pedestrian footsteps, wheel loads, and vibration.

a) Ceramic-Coated PZT Diaphragms

These sensors consist of piezoelectric ceramic elements pressed onto a brass substrate and are widely known for producing high output voltages under low-frequency dynamic loading conditions Pan *et al.* (2019). The piezoelectric element has a metal plate diameter of 20 mm, a piezoelectric ceramic diameter of 14 mm, an electrode diameter of 12.8 mm, a 0.20 mm thick brass substrate, and a piezoelectric layer thickness of 0.42 mm. These diaphragms were utilized in both standalone configurations and series-connected modular systems.

b) 5 cm Large-Diameter PZT Sensor with a Brass Substrate

Due to their larger surface area, these sensors have the potential to generate higher voltage levels even under low-pressure conditions. In asphalt-embedded applications, large-diameter sensors can provide more stable signals when embedded closer to the pavement surface (Jung *et al.* 2017).

c) 3 cm Diameter Series-Connected Dual PZT Module

Due to their relatively small surface area, these sensors produce low energy output when used individually; therefore, two sensors were connected in series to increase the output voltage (Song *et al.* 2019).

d) Vibration-Based PZT Cantilever Sensors

The MIDE PPA-1014 piezoelectric cantilevers used for the field experiments are devices optimized for harvesting energy from vehicle-induced vibrations (Wang *et al.* 2020). The piezoelectric element is based on a PZT-5H piezoceramic material and features an active area of 500 mm^2, a sensitivity of 56 mV/g, a capacitance of 24 nF, and a maximum operating voltage of 500 V. The selection of cantilevers was intended to prevent sensor failure caused by direct wheel loads and to enhance the effectiveness of vibration-based energy harvesting (Wu *et al.* 2018).

Vibration Base Plate: Due to the brittle nature of piezoelectric ceramics, a phosphor bronze layer was added beneath the sensors. This material provides high elastic deformation capacity, excellent fatigue resistance, good electrical conductivity, and corrosion resistance, making it well suited for long-term piezoelectric energy harvesting applications. Accordingly, it was selected based on these advantageous properties (Papagiannakis *et al.* 2017). The dimensions of the piezoelectric element are 4 cm in width and 0.3 mm in thickness. This layer enables the sensor to undergo maximum deformation under load to generate optimal voltage output while preventing mechanical damage.

Adhesive and Interface Materials: DB2011 copper powder–based conductive resin was selected because of its high electrical conductivity, good shear strength, moderate elasticity, and thermal stability, ensuring both reliable electrical connections and mechanical durability. In addition, cyanoacrylate adhesive was used to provide high bonding strength, rapid curing, and sufficient mechanical support for the assembly of the piezoelectric components. This dual-layer configuration allows the sensor to be electrically connected while also being mechanically secured (Moure *et al.* 2016).

Testing Process, Parameters, and Tools

Marshall Specimens: In the asphalt-based experiments, Marshall specimens were prepared using 1200 g of aggregate and 5% bitumen. The procedure was conducted in accordance with ASTM D1559 (Hong *et al.* 2021).The specimens were prepared with a height of 6.0–6.5 cm and compacted using 75 blows under controlled temperature conditions. In addition, special protective interface layers were incorporated during specimen preparation to prevent damage to the piezoelectric sensors during installation. The selection of bitumen content was based on the optimum proportions reported in the study by (Yang *et al.* 2017).

Table 2 Test Specimens and Embedded Piezo Configurations

Specimen Code	Embedding (cm)	Depth	Piezo Diameter	Piezo Configuration	Connection Type	Description
M - 1	6.5		5 cm	Single sensor	Parallel	Placement close to the upper layer
M - 2	4.5		5 cm	Single sensor	Series	Embedded closer to the surface
M - 3	6.5		3 cm	Two sensors	Series	Increased energy density
M - 4	5.0		5 cm	Single sensor + plywood	Parallel	Insulation to prevent grounding
M - 5	3.5		3 cm	Triple sensor array	Series - Paralel	Sidewalk-type application

Experimental Design and Analyses

Experimental Setup 1: In this setup, two different specimens were prepared: one incorporating a single 5 cm PZT sensor and another incorporating two 3 cm diameter sensors connected in series. To prevent sensor damage during the embedding process, a 0.5 cm thick mastic layer was applied to the bottom surface, a 10 cm diameter cork disk was placed on the top surface, and the load was applied in a controlled manner. Voltage measurements were subsequently performed using a Fluke digital multimeter under both manual pressing and impact loading conditions, with the latter applied using a wooden mallet.

Experimental Setup 2: This method aims to increase the output voltage by reducing the embedding depth of the piezoelectric sensors. Three sensor configurations were investigated: a 5 cm sensor embedded at depths of 6.5 cm and 4.5 cm, and a 3 cm sensor embedded at a depth of 6.5 cm. The bottom surface consisted of a 3 mm plywood layer, a 3 mm cardboard layer, and an insulating layer to eliminate grounding effects. To prevent sensor fracture during the compaction process, a 1.5 cm thick rubber protective layer with a diameter matching that of the mold was placed on the top surface. Output voltages were subsequently measured under impact loading using a modified Proctor hammer.

Pedestrian-Induced Energy Harvesting Module

This system was specifically designed for energy generation in areas with high pedestrian traffic (e.g., mosque courtyards, metro stations, and campus walkways).

Mechanical Architecture of the Module: The module consists of three assembled plates: a top cover measuring 455 × 405 × 15 mm, a bottom base measuring 455 × 405 × 3 mm, and an intermediate

plate measuring 420 × 380 × 12 mm. Footstep forces applied to the top surface were transmitted to the piezoelectric sensors through hot silicone rods. A total of fourteen sensors were uniformly arranged in a circular configuration to ensure an even distribution of the applied load.

Electrical Power Conversion System

Bridge Rectifier Design: The 1N60P Schottky diode was selected because of its low forward voltage drop (0.24 V), suitability for high-frequency applications, and low thermal loss. The rectifier circuit was configured using four Schottky diodes and a 2.2 μF filter capacitor to ensure efficient AC–DC conversion and output voltage smoothing.

DC–DC Buck Converter: The output of the piezoelectric sensor is inherently variable and irregular, typically consisting of a low-frequency mixed AC/DC signal fluctuating between 0 and 20 V. To obtain a stable output voltage of 5 V, the system incorporates a buck converter regulated by a PI-based Two-Loop Cascade Control (TLCC) strategy. The control architecture consists of an outer voltage loop and an inner current loop, while the controller parameters were tuned using the Ziegler–Nichols method (Sharuddin *et al.* 2020).

Field Tests Conducted Under Vehicle Loads

The real-field test was conducted at an automated toll booth on the BR-290 Federal Highway in Brazil. Vehicle loads provided an ideal environment for triggering sensor vibrations and inducing resonance in the cantilevers (Ke and Wang 2012).

Design of the Prototype Housing: Four metal housings were fabricated, each containing four cantilever structures, resulting in a total of 16 piezoelectric sensors. The housings were equipped with waterproof top covers and installed flush with the concrete surface to ensure structural integrity and effective load transfer. In addition, an elastomeric filler material was applied between the housings to improve sealing and accommodate mechanical deformation.

Loading Scenarios: Two different tip masses were evaluated at the free ends of the cantilevers to investigate their influence on energy harvesting performance. An initial tip mass of 6.7 g was employed as a safe loading condition during the preliminary tests, whereas a larger tip mass of 16 g was subsequently introduced to increase cantilever deformation and enhance electrical energy generation.

DISCUSSION

This study comprehensively investigated the potential of piezoelectric flooring systems to harvest energy from human footsteps and low-frequency mechanical excitations, revealing the electrical, mechanical, and dynamic behavior of the system through both laboratory data and circuit-based performance measurements. When the obtained results are compared with the existing literature, the prototype developed in this study is observed to deliver significantly more stable and higher power outputs than comparable piezoelectric sidewalk systems.

Interaction Between Load and Frequency and the Piezoelectric Response Mechanism

During the loading tests conducted under laboratory conditions, a pronounced increase in current values was observed as the applied loading frequency increased, whereas the voltage levels exhibited a more limited variation. This behavior can be attributed to the rate dependent separation of charge carriers within the piezoelectric crystal, leading to an increase in surface charge density. In accordance with the positive piezoelectric effect, the amount of generated charge is directly proportional to the applied force (Gammaitoni 2012).

Similarly, the observed increase in current under high-frequency loading conditions has also been confirmed in the literature, particularly in studies focusing on roadway surface vibration energy harvesting (Moure *et al.* 2016). However, the results obtained in this study indicate that increasing the loading frequency does not lead to a significant increase in voltage output. This behavior can be explained by the small thickness of the piezoelectric disks, which allows them to rapidly reach their maximum deformation level even under relatively low loads. Previous studies have likewise reported that thin PZT disks exhibit a "rapid saturation behavior" (Gholikhani *et al.* 2020; Ting *et al.* 2012). In this context, to improve system efficiency, the use of thicker piezoelectric layers or multilayer composite piezoelectric structures may be considered in future work.

Energy Density Analysis and the Realistic Constraints of Human Footstep Energy Harvesting

The average peak voltage generated from a single pedestrian step was measured as 2.4 V, with a corresponding current of approximately 79 µA, resulting in an instantaneous peak power of 0.19 mW. Assuming an average excitation duration of 0.2 seconds per step, the estimated harvested energy per pedestrian event is approximately 38 µJ.

This observation is consistent with the literature, which indicates that piezoelectric energy harvesting becomes more efficient when implemented using multi-sensor arrays in areas with high pedestrian traffic (Pan *et al.* 2019; Jung *et al.* 2017). Studies conducted in locations such as Al-Haram, major stadium entrances, and metro transfer hubs report that piezoelectric systems can generate power at the watt level when daily pedestrian flow is sufficiently high (Song *et al.* 2019). From this perspective, the results of this study indicate that although the output of an individual sensor is low, it has the potential to translate into meaningful power generation when the system is implemented in a modular and scalable configuration. From a theoretical standpoint, the instantaneous electrical power generated by the piezoelectric module can be expressed as:

$$P = \frac{V^2}{R} \tag{1}$$

where V is the measured voltage across the load resistance R. The harvested energy per excitation event is calculated as:

$$E = P \times t \tag{2}$$

where t represents the effective load duration. Additionally, the constitutive behavior of piezoelectric materials can be described by:

$$D = dT + \varepsilon E \tag{3}$$

where D is the electric displacement, d is the piezoelectric coefficient, T is the applied mechanical stress, ε is the permittivity, and E is the electric field. These relationships provide the theoretical basis for the experimentally observed voltage and current behavior under pedestrian-induced loading.

Testing of the Rectification Circuit and the Behavior of LED Loads

The observation of a peak open-circuit voltage of 33.7 V confirms that piezoelectric disks characteristically produce high voltage but low current due to their high internal impedance (Wang *et al.* 2020). In the LED load tests, the proposed piezoelectric energy harvesting system generated an output of 2.4 V and 79 μA when driving a single LED, corresponding to an output power of approximately 0.19 mW. For two LEDs connected in series, the measured output voltage increased to 4.8 V, whereas a parallel connection maintained an output voltage of 2.4 V. These results demonstrate the capability of the proposed system to supply sufficient electrical power for low-power LED applications under different loading configurations.

These results are consistent with studies reporting that LED driving is feasible in piezoelectric-based energy harvesting prototypes (Pirisi *et al.* 2013). However, the obtained power output of 0.2496 mW falls within the low-milliwatt range typically observed in single-module piezoelectric sidewalk systems. Higher power levels reported in the literature (50–200 mW) are generally achieved through larger arrays, optimized mechanical amplification mechanisms, or high-density traffic conditions (Gholikhani *et al.* 2019).

Performance of Voltage Regulation Using a DC–DC Converter

Since piezoelectric energy harvesting systems inherently generate irregular and fluctuating output signals, maintaining a stable output voltage remains a major challenge. To address this issue, the proposed system incorporates a DC–DC buck converter regulated by a Two-Loop Cascade Control (TLCC) strategy. Experimental results demonstrate that the controller successfully maintained a constant output voltage of 5 V, even when the input voltage fluctuated between -20 V and $+20$ V, thereby ensuring stable power delivery for low-power electronic applications.

This result is consistent with active control methods recommended in the literature for low power renewable energy sources (Wang *et al.* 2016). The PI control gains determined using the Ziegler Nichols method enabled the system to respond rapidly and stably to sudden load variations. Accordingly, the proposed control approach helps mitigate one of the key sustainability challenges associated with piezoelectric energy harvesting circuits.

Analysis of Practical Feasibility and Potential Energy Usage Scenarios

The measured peak power levels remain within the low-milliwatt range, which is sufficient to support the intermittent operation of ultra-low-power IoT devices. Potential applications include security cameras, LED guidance modules, wireless sensors, traffic counters, air quality monitoring devices, and low-power signal transmitters, demonstrating the practical applicability of the proposed piezoelectric energy harvesting system in smart city infrastructure. Similar applications have been successfully implemented in roadside systems in the literature, and prototypes in which entire sensor networks are powered by piezoelectric energy have been reported (Liu *et al.* 2018; Ambrozkiewicz *et al.* 2021; Qin *et al.* 2022).

Material Strength, Structural Constraints, and Deformation Challenges

During the experiments, it was observed that piezoelectric disks exhibited a high risk of fracture under excessive pressure. The observed behavior can primarily be attributed to the low thickness of the piezoelectric sensor, the relatively weak mechanical integration between the metal and ceramic layers, the high local load concentration, and the low mechanical resonance stiffness. These factors collectively limit the mechanical durability and energy conversion performance of the sensor under repeated loading conditions. Following mechanical reinforcement, the sensors produced strong and stable outputs at the milliwatt level. Similarly, numerous studies have reported that piezoelectric disks with thin ceramic layers commonly exhibit cracking, fatigue, and surface degradation (Duc *et al.* 2022; Thai *et al.* 2021).

The System's Scalability Potential

The use of 14 sensors within a single sidewalk module demonstrates that the system is scalable through multiple rectification stages as well as parallel or series connection configurations. For example, in a deployment consisting of 100 modules, the cumulative energy yield can be significantly increased under ideal aggregation conditions and by neglecting power conversion losses. Although the overall system output remains within the low-power micro-generation range, it may be sufficient to support the continuous operation of low-power street lighting systems or distributed sensor networks. These results demonstrate the scalability and practical potential of modular piezoelectric energy harvesting systems for smart city infrastructure.

Future Enhancement Suggestions

Based on the limitations of this study and the experimental findings, several directions for future research are recommended to improve the performance and practical applicability of piezoelectric energy harvesting systems. Sensor optimization may be achieved through the use of multilayer PZT structures, thick-film piezoelectric materials, piezoelectric fiber composites, and hybrid PVDF–PZT sensors to increase energy density and conversion efficiency. From a mechanical perspective, the incorporation of load distribution plates, elastomer-based shock-absorbing layers, and resonance-enhanced structural designs could improve load transfer, mechanical durability, and energy harvesting performance.

In addition, the electronic subsystem can be enhanced by integrating Maximum Power Point Tracking (MPPT) algorithms, intelligent energy storage units, and adaptive load management modules to maximize energy utilization and ensure stable power delivery. Finally, future studies should focus on long-term field validation through 6–12 months of continuous monitoring under high pedestrian-density conditions, together with comprehensive evaluations of water resistance, humidity resistance, and the effects of temperature variations on system reliability and durability.

Table 3 Literature Comparison on Piezoelectric Energy Harvesting

Study	Piezoelectric Type Used	Test Configuration	Maximum Output (V)	Power (mW)	Key Findings
Li et al. Gammaitoni (2012)	PZT-5H ADB	Laboratory test – 0.96 mm displacement	49.8	1235	Voltage increased by 356% using ADB
Kim - Kim Moure *et al.* (2016)	Rotary generator	Vehicle suspension system	-	59.45	High power generation from vehicle vibrations
Santos et al.	PZT cantilever	Highway prototype	-	0.68	Low power output with 11 months of durability
Mahmoud et al. Ambrozkiewicz *et al.* (2021)	PZT diaphragm	Sidewalk / floor tile	33.7	249.6	Successful driving of two LEDs
Alshammari - Khalid Yang *et al.* (2019)	Hybrid (Piezo + Solar)	Al-Haram case study	-	3-12	Suitable for high pedestrian and traffic density areas

CONCLUSION

It should be noted that the reported values correspond to peak instantaneous measurements obtained under controlled experimental conditions. Variations in pedestrian weight, stepping frequency, environmental conditions, and long-term material fatigue may influence the effective energy yield in real-world deployments. Future studies should incorporate statistical repeatability analysis, uncertainty quantification, and long-term performance monitoring to further validate system robustness. The literature reviewed, experimental prototypes, and field implementations examined within the scope of this study indicate that piezoelectric-based energy harvesting technologies are technically feasible and show promising potential under both pedestrian and vehicular traffic conditions. The findings suggest that similar trends are reported across different research groups, and that piezoelectric systems may represent a viable option for energy generation as well as for addressing the sensor requirements of smart transportation infrastructures.

Table 4 Energy Harvesting Test Results

Loading Type	Maximum Voltage (V)	Current (μA)	Power (mW)	Measurement Method
Single step (pedestrian)	2.4	79	0.1896	Voltage measurement (Oscilloscope)
Series LED load (2 units)	4.8	52	0.2496	Voltage measurement (Oscilloscope)
Vehicle load (wheel pressure)	61.6	112	6.899	Voltage measurement (Multimeter, OC)
Finger compression test	61.6	103	6.348	Voltage measurement (Multimeter, OC)
Finger impact	59.2	95	5.624	Voltage measurement (Multimeter, OC)

The voltage values reported in Table 4 were directly measured between the output terminals of the piezoelectric module under both open-circuit (OC) and loaded conditions. The corresponding current values were calculated using Ohm's law based on the measured voltage across the known load resistance. Consequently, the reported power values represent instantaneous peak power rather than continuous output power. It should be emphasized that the actual usable energy depends on the duration of the applied load as well as the efficiency of the rectification and energy storage circuitry. This calculation approach is widely adopted in piezoelectric energy harvesting studies due to the inherently high internal impedance of piezoelectric devices.

Across various experimental studies reported in the literature particularly those focusing on energy harvesting from human footsteps and low-amplitude vibrations, piezoelectric elements have been shown to produce peak voltages in the range of 20–33 V. With appropriate rectification and power-conditioning circuits, these voltage levels can be regulated to obtain a stable 5 V DC output suitable for low-power electronics. In previously reported large-area flooring prototypes (e.g., panels measuring approximately 455 × 405 mm), individual modules have been demonstrated to power LED loads, while multi-panel systems operating under high pedestrian density have achieved energy yields on the order of tens of watt-hours over extended operating periods. Such results highlight the potential of large-scale deployments as micro-generation solutions in locations characterized by sustained pedestrian flow, including institutional entrances, campuses, public transportation hubs, and metro stations.

Similarly, piezoelectric systems operating under vehicular traffic have demonstrated a higher energy generation capacity due to increased loading levels. In prototype-scale field implementations, PZT cantilever-based systems have been shown to continuously harvest energy at approximately 50 mWh per month from high-speed vehicle traffic, a level sufficient to power LED road markers or low-power sensor systems along a 200 m roadway segment. Moreover, the high durability exhibited by systems incorporating 16 piezoelectric cantilevers indicates that such configurations can be integrated into long-lasting infrastructure components. Experimental measurements demonstrate that each pedestrian step generates approximately 30–40 μJ of recoverable energy under controlled laboratory conditions. The associated peak power reaches approximately 0.19 mW; however, this value corresponds to instantaneous output rather than sustained power delivery. When accumulated over multiple pedestrian events, the harvested energy becomes sufficient to operate low-power electronic devices such as LEDs, temperature–humidity sensors, and IoT modules.

Due to the inherently low-current–high-voltage characteristics of piezoelectric systems, hierarchical energy management architectures incorporating rectification, filtering, and DCDC conversion stages are required. Simulation results further confirm that the two-loop cascade control (TLCC) strategy maintains a regulated 5 V output under dynamic input voltage fluctuations. When large-scale energy harvesting potential is considered, the importance of hybrid systems becomes particularly evident. While standalone piezoelectric elements exhibit limited power generation capability, hybrid systems that integrate piezoelectric components with triboelectric generators (TENGs), electromagnetic sensors, and photovoltaic surfaces have been shown to significantly enhance energy output, especially in areas with high pedestrian traffic. Evaluations conducted for locations with extremely dense pedestrian flow, such as the Al-Haram Mosque, indicate that the combined use of piezoelectric, triboelectric, and photovoltaic modules can enable the development of stable, continuous, and modular energy generation infrastructures.

In addition, piezoelectric materials based on PVDF, $BaTiO_3$, and MXene have been shown to exhibit longer service life and higher durability compared to conventional PZT elements, owing to their enhanced flexibility and fatigue resistance. Furthermore, cellulosic, biomimetic, and additively manufactured (3D-printed) composite structures are considered to represent an important development pathway for next-generation smart flooring systems.

Nevertheless, piezoelectric energy harvesting systems continue to face several important challenges that limit their widespread implementation. First, the energy generated by individual piezoelectric units remains relatively low, making standalone systems insufficient for high-power applications and highlighting the need for hybrid energy harvesting approaches. Second, long-term performance is strongly influenced by environmental factors such as temperature fluctuations, humidity, material fatigue, and repeated mechanical loading, all of which may reduce system reliability and energy conversion efficiency. Finally, the integration of piezoelectric devices into existing pavement and flooring infrastructure presents additional challenges related to structural durability, maintenance requirements, and their potential impact on pavement service life. Addressing these issues will be essential for the large-scale deployment of piezoelectric energy harvesting systems in future smart city environments.

Despite these challenges, the body of literature consistently indicates that piezoelectric-based energy harvesting is highly viable for low-power applications, aligns well with smart city visions, and is expected to play an important role in sustainable infrastructure projects. Applications such as smart lighting systems, road marking LEDs, traffic signalization, wireless sensor networks, IoT-based data acquisition systems, and security cameras can all be

supported by energy harvested from piezoelectric panels.

This study experimentally quantified a peak energy of approximately 38 μJ per pedestrian step and demonstrated stable 5 V voltage regulation under ±20 V input fluctuations using TLCC control. In conclusion, piezoelectric energy harvesting represents an economical, environmentally friendly, sustainable, and low-maintenance method of electricity generation. Owing to the scalability of systems deployed in high-traffic areas, their potential to reduce energy costs, and their alignment with carbon-neutral city objectives, piezoelectric energy harvesting is a strong candidate to become a core component of future smart transportation infrastructures. In future studies, the development of higher-efficiency piezoelectric materials, the integration of deep learning–based energy management systems, and the wider adoption of hybrid energy harvesting solutions are expected to further enhance the large-scale applicability of this technology.

In parallel with this study, research and development activities related to the proposed piezoelectric sidewalk concept are ongoing. Future work is expected to focus on exploring sensor configurations with higher energy density, investigating the integration of hybrid energy harvesting approaches (piezoelectric–triboelectric–photovoltaic), performing longterm field evaluations, and examining scalable modular system designs. These efforts are intended to improve energy generation efficiency while facilitating the reliable and sustainable integration of the system into smart city infrastructures. In this context, the present study aims to provide a preliminary foundation that may support the future development and application of piezoelectric-based flooring energy harvesting technologies.

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Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

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The Future of Banking Services in the Era of Digital Financial Ecosystems

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ABSTRACT The rapid digital transformation of banking services is fundamentally changing the banking sector. This change is driven by new technologies such as artificial intelligence, blockchain, cloud computing and open banking platforms. Traditional banking models are becoming more agile and customer-centric systems. These systems are focused on seamless digital experiences, real-time services and data-driven decisions. This change has also led to the development of the digital finance ecosystem. This ecosystem is an integrated network in which financial and non-financial services, platforms and technology companies collaborate to deliver comprehensive and personalized value to users. It extends beyond traditional banking boundaries, incorporating fintech firms, technology providers, regulators and third-party service platforms. This article examines the future development of banking services within the context of this digital financial ecosystem. It also analyzes how banks can adjust their strategies, processes and business models to adapt to this environment. The study employs a qualitative research methodology that combines a systematic literature review with case studies of main digital banking platforms and financial institutions leveraging this ecosystem. The findings suggest that, in order to fully participate in the digital financial ecosystem, banks must adopt platform models, invest in innovative technologies and strengthen their strategic partnerships. Furthermore, regulatory compliance, cybersecurity and customer trust emerge as crucial factors for the sustainability of this ecosystem. This study expands upon existing research by presenting a conceptual framework for understanding ecosystem-driven banking innovation and offers practical insights into the path financial institutions should take in a complex and constantly evolving environment.

KEYWORDS
Blockchain
Cloud computing
Cybersecurity
Open banking
Digital banking technologies

INTRODUCTION

The global banking industry is experiencing major changes as digital technologies continue to change the way banking services are designed, delivered and consumed. Over the past decade, the rapid adoption of digital banking, online platforms and data-driven solutions has changed customer expectations. Today, customers want faster, more personalized and seamlessly connected banking services. Traditional banks, once known for their physical branches and standard services, are now required to become digital organizations. They need to operate successfully in a rapidly changing and highly competitive environment. This change is also due to the growth of fintech companies and technology firms. These companies provide innovative solutions and increase competition for traditional banks.

In this environment, the idea of a digital financial ecosystem has become an important model for the future of banking services. A digital financial ecosystem is a network of interconnected platforms, institutions and service providers. They collaborate together to provide a wide range of financial and non-financial services through a shared digital infrastructure. The ecosystem uses open banking, APIs (application programming interfaces) and cloud technologies to support seamless collaboration between different participants. These include banks, fintech companies, regulators and customers. As a result, the boundaries between industries are becoming increasingly blurred. This shift is creating new business models focused on collaboration, platform development and shared value creation.

As the digital financial ecosystem becomes more important, questions arise about the role of banks in this changing environment. Banks need to rethink more than just the use of advanced technologies. They also need to consider their market positions, organizational structures and relationships with customers. At the same time, issues such as privacy, security, regulatory compliance and trust are becoming more complex. An interconnected ecosystem requires close collaboration between many different actors. This paper aims to examine the future of banking services in the era of the digital financial ecosystem. It also seeks to better understand the opportunities and challenges created by this transformation. By examining current trends, technological developments and new business models, the article intends to contribute to academic debates and support practical decision-making in the banking sector.

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LITERATURE REVIEW

Literature on the digital transformation of banking services emphasizes the growing importance of digital financial technologies as a main driving force behind structural changes in the banking sector. Fintech means improving or changing traditional financial services by using modern digital technologies such as artificial intelligence, blockchain, big data analytics and mobile platforms (Nguyen and Phong 2026). Fintech companies help improve efficiency, lower transaction costs and increase financial inclusion. At the same time, large technology companies possessing vast digital infrastructure and customer bases are entering the banking sector. They do this by adding banking services to their existing digital platforms. This trend is closely linked to the growth of the platform economy, where digital platforms act as intermediaries between different users and service providers. They enable value creation through scalable networks.

The shift from traditional banking to ecosystem-based banking represents a major change in how banking services are organized and delivered. Traditional banking models had vertically integrated structures, limited ways of interacting with customers and a product-centric approach. However, the development of open banking platforms and API-based infrastructure has enabled banks to become more collaborative and agile systems (Ghosh and Golder 2026). The ecosystem is a financial services model in which banks, fintech companies, third-party service providers and non-financial institutions operate together as an interconnected network. They deliver integrated services through a shared platform. This evolution reflects broad trends such as decentralization, interoperability, and customer-centric innovation.

Understanding the digital financial ecosystem requires various theoretical approaches. Platform theory explains value creation through multifaceted markets and network effects. It also suggests that digital platforms play a strategic role by coordinating activities within the ecosystem. Diffusion of innovation theory illustrates how new financial technologies are adopted over time by banks and customers. Furthermore, resource-based theory and dynamic capability theory demonstrate the importance of organizational adaptability, technological capability and strategic partnerships to achieve competitive advantage in a rapidly changing ecosystem. Institutional theory plays a crucial role in explaining the impact of regulatory frameworks and standards on the development and governance of digital financial systems (Akyildirim *et al.* 2025).

Although previous studies have examined banking digitalization, open banking, fintech collaboration and platform-based services, they have mostly examined these topics separately. Only a limited number of studies integrate these aspects into a single conceptual model of ecosystem banking. Existing frameworks have mainly focused on technological innovation or regulatory issues. They pay less attention to the relationship between technological infrastructure, ecosystem governance, strategic partnerships, customer value creation and sustainable performance.

The conceptual framework proposed in this study fills this gap by integrating technological, strategic, organizational and regulatory perspectives into a single analytical model. Unlike previous studies that have described ecosystem components in isolation, the proposed framework illustrates how digital technologies, ecosystem participants, governance mechanisms and customer-centric value creation work together to shape the future of banking services. As a result, the framework offers both theoretical integration and practical guidance. It helps banks transform from traditional service providers to ecosystem coordinators.

METHODOLOGY

This paper applies qualitative research methods to explore the transformation of banking services within the context of digital financial ecosystems. A systematic literature review was conducted, using recent academic studies, articles, and reports. The main academic sources were publications indexed in Scopus, Web of Science, ScienceDirect, and SpringerLink. Only peer-reviewed journal articles published between 2020 and 2026 were selected. This helped ensure that the study reflects recent developments in digital banking. Studies that focused solely on the software application and did not discuss banking digitalization were excluded. Greater attention was given to highly cited articles published in leading journals in the fields of banking, finance and digital innovation.

A thematic analysis was used to integrate data and case studies from the selected literature. Similar findings were grouped into common themes. These recurring themes were then incorporated into the conceptual framework presented in this study. The aim of this article is to explain the concept of ecosystem banking. It also aims to identify the role of main banking technologies, along with their benefits, challenges and risks. It also highlights future trends in banking ecosystems. The discussion section also provides recommendations for banks and regulators based on international experience. Here, the impact of ecosystem banking on customers and businesses are further highlighted. Although this article is largely based on secondary data sources, it provides a clear and detailed overview of the expected changes in banking services within digital financial ecosystems. It also discusses developments that are likely to occur in the near future.

RESULTS

Transformation of Banking Services

According to empirical and conceptual analyses, banking services are undergoing a major transformation. They are moving from a product-centric to a customer-centric model. Traditionally, banks focused on standardized financial products. However, with the growth of the digital ecosystem, value creation is now focused on providing a complete customer experience. This change is driven by higher customer expectations for convenience, speed and personalized services. This is also supported by increased competition from fintech companies and digital platforms. One of the main elements of this transformation is the delivery of personalized banking services through advanced data analytics (Figure 1). Banks can use customer data to predict customer needs, recommend relevant products and increase customer engagement through real-time decision-making (Chan *et al.* 2022).

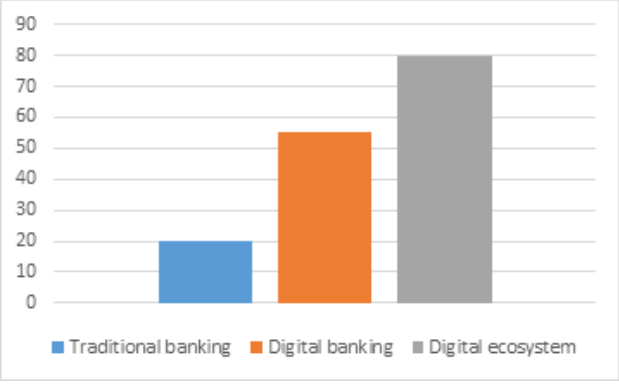

Figure 1 Degree of personalization by banking model

In addition, the growth of integrated financial services is changing the way people access and use banking services. Financial services are now seamlessly integrated with non-financial platforms. In particular, "super-applications" help increase customer loyalty. They also reduce dependence on separate platforms by integrating multiple services into a single digital interface.

The Role of Digital Technologies

The findings of this study highlight the important role of digital technologies in the implementation of ecosystem-based banking. Artificial intelligence (AI) is widely used to improve operational efficiency and support data-driven decision-making. It is particularly useful in credit scoring, fraud detection and automated customer service (Alnaser *et al.* 2023). AI-based systems allow banks to move from passive to proactive service delivery. As a result, they increase both efficiency and customer satisfaction (Table 1).

Table 1 Key technologies and their functions

Technology	Primary Function	Impact on Banking
AI	Predictive analytics, automation	Personalization, efficiency
Blockchain	Decentralized ledger	Security, transparency
Cloud Computing	Scalable infrastructure	Cost reduction, flexibility
Open Banking APIs	System integration	Innovation, collaboration

Blockchain technology increases trust and transparency within the digital ecosystem by providing secure and decentralized transaction records (Patel *et al.* 2022). This is especially important for cross-border payments, identity verification and smart contracts. Cloud computing provides the infrastructure needed for digital transformation. It supports rapid innovation and provides scalable, flexible and cost-effective solutions (Cheng *et al.* 2022). Furthermore, Open Banking APIs improve interoperability between ecosystem participants. They enable seamless service integration and encourage collaborative innovation.

Benefits of Ecosystem-Based Banking

Research shows that ecosystem-based banking creates significant value in several ways, as given in Figure 2.

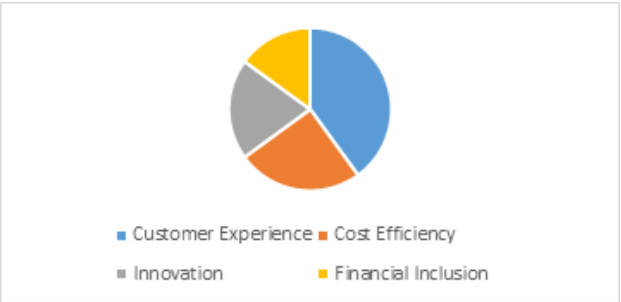

Figure 2 Benefits distribution

First, it significantly improves the customer experience by offering integrated, seamless and context-specific services. Customers gain easier access to financial and non-financial services through a single interface. This also increases overall accessibility (Soyupak and Ipek 2025).

Second, ecosystem participation increases cost efficiency. Banks can reduce operational costs and use resources more efficiently by leveraging shared infrastructure, automation technologies and strategic partnerships (Calzada and Pablo 2026). Third, digital ecosystems promote financial inclusion by expanding services to underserved populations. These are people with limited access to banking services, especially in regions with high mobile phone usage (Ryan and Mukherjee 2026). Finally, collaboration among the various ecosystem participants accelerates innovation. It also supports the development and implementation of new products and services.

Challenges and Risks

Despite numerous advantages, the findings highlight several critical challenges and risks associated with the ecosystem-based banking (Table 2).

Table 2 Main challenges and implications

Challenge	Description	Implication
Cybersecurity	Increased attack surface	Higher operational risk
Data Privacy	Data misuse concerns	Loss of customer trust
Regulation	Fragmented legal frameworks	Compliance costs
BigTech Competition	Market dominance of tech giants	Reduced market share

Cybersecurity has become a major concern due to greater system interconnection and the expanding attack surface (Modesti *et al.* 2025). As banking services become more digital, the risk of data breaches, fraud and cyberattacks continues to increase. This highlights the need for strong security measures and continuous system monitoring.

Data protection is also a major challenge, as the ecosystem model relies heavily on the collection, sharing and analysis of vast amounts of customer data. Banks struggle to maintain customer trust while complying with data protection regulations. Furthermore, the ecosystem model increases regulatory complexity. This is because many different participants operate in different countries and legal frameworks (Horobets *et al.* 2025). Competition from technology companies further exacerbates these challenges. These companies have advanced technology, access to vast amounts of customer data and strong digital platforms. Their entry into the banking services market increases competitive pressure on traditional banks. As a result, smaller banks may face lower profits and the market may become more concentrated.

Regional Perspectives

The analysis reveals significant regional differences in the adoption and development of digital financial ecosystems. Developed markets have reached a high level of ecosystem maturity. This is supported by a robust technological infrastructure, effective regulatory frameworks and a high level of digital literacy among consumers. These factors encourage rapid adoption of innova-

tion and support the growth of ecosystem-based banking models (Figure 3).

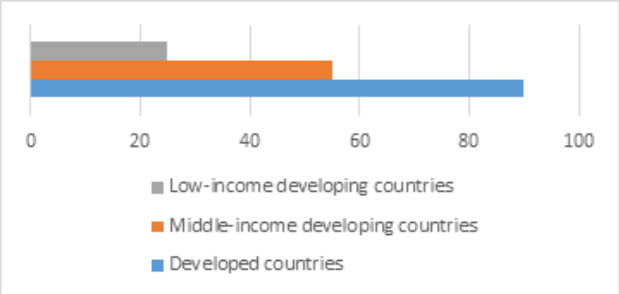

Figure 3 Ecosystem maturity by region

In contrast, emerging markets hold strong growth potential, driven by expanding mobile connectivity and increasing demand for accessible banking services. (Nandy *et al.* 2025). However, these markets often face challenges such as regulatory uncertainty, limited infrastructure and differences in digital readiness. Emerging markets, while still in their early stages, have the opportunity to improve traditional banking models by implementing mobile-first and digital platform solutions.

Future Trends in Banking Ecosystems

Several important trends are expected to shape the future of the banking ecosystem.

Table 3 Key future trends and their impact

Trend	Description	Expected Impact
DeFi	Decentralized financial services	Reduced intermediaries
Platformization	Banking as a platform	Diversity, Convenience
AI-driven banking	Autonomous decision-making	Increased efficiency
Cross-industry ecosystems	Integration with other sectors	New business models

The most significant is the rise of decentralized finance (DeFi). Using blockchain technology, DeFi enables peer-to-peer financial transactions without the need for traditional financial institutions. It has the potential to change traditional banking models and reshape the role of financial institutions. Another important trend is the integration of banking services into digital platforms. Banking functions are becoming part of larger digital platforms and are offered as modular services. At the same time, advances in artificial intelligence are supporting the development of autonomous banking systems. These systems can make financial decisions in real time with minimal human intervention (Polireddi 2024).

Finally, the emergence of cross-sector ecosystems is becoming an important trend. These ecosystems bring together finance, e-commerce, telecommunications and mobile technologies. This represents a major shift towards integrated value creation. By moving beyond traditional structures and offering a broader range of services, these ecosystems can improve customer engagement and create new revenue opportunities (Table 3).

DISCUSSION

The findings of this study show that the transition to a digital financial ecosystem is not just a technological change. It is also a major transformation of banking operations. As banking services become part of broader digital platforms, banks, regulators and market participants need to rethink their roles, strategies and interactions. This section discusses the practical implications of these findings. It also provides recommendations for main participants.

Recommendations for Banks

The findings suggest that banks need to adopt comprehensive and forward-looking digital strategies to remain competitive in this ecosystem. These strategies should not only focus on digitizing existing services. They should also support the development of platform-based business models. This includes investing in scalable digital infrastructure, improving data analytics capabilities and increasing organizational agility (He *et al.* 2023). Banks should focus on customer-centric innovation and use data to deliver personalized and relevant services. In addition, digital strategies should be aligned with long-term business objectives. This is essential for creating sustainable value.

Another important recommendation is for banks to establish strategic partnerships with fintech companies. Banks should work with fintech firms rather than treating them as competitors. These partnerships can help banks gain access to new technologies, accelerate product development and expand their service offerings. Partnerships can take a variety of forms, including joint ventures, API integration and innovation labs (Ryan and Mukherjee 2026). By taking an active role in the digital ecosystem, banks can strengthen their market position. They can also strengthen their role as primary players.

Recommendations for Regulators

As the digital financial ecosystem continues to evolve, regulators need to take a flexible and forward-looking approach. A main priority is to create and implement a strong open banking framework. This framework fosters competition and innovation. It enables secure data sharing between financial institutions and third-party providers through standardized APIs. Effective open banking policies can support ecosystem growth while ensuring fair competition among all participants (Tsai *et al.* 2024).

At the same time, data protection and privacy policies need to be strengthened. This is necessary because the amount and sensitivity of customer data in the digital ecosystem continues to grow. Regulators should set clear rules regarding data ownership, consent management and cross-border data sharing. Enforcing these rules is essential to maintain customer trust and protect the stability of the financial system. Furthermore, regulatory testing environments and innovation-friendly policies can encourage experimentation. They can also help reduce systemic risks.

Impact on Customers and Businesses

The shift to ecosystem-based banking has a major impact on both customers and businesses. For customers, the integration of banking services into digital ecosystems provides greater convenience, more personalized experiences and broader access to financial products. However, concerns about privacy, security and transparency are also growing. These issues require careful monitoring by both service providers and regulators (Wang 2025). For businesses, especially SMEs, the digital financial ecosystem creates new opportunities. This improves access to financing, payment solutions and other supporting services. Integrating financial products

with business platforms can improve operational efficiency and support faster growth. However, intense competition and greater reliance on digital platforms also create strategic challenges. Businesses need to adapt to a rapidly changing market environment (Said *et al.* 2026). Overall, this discussion emphasized that the success of the digital financial ecosystem depends on collaboration between banks, regulators and market participants. A balanced approach, promoting innovation while ensuring safety, security and inclusion, will be essential to guide the future development of the banking sector.

Comparison with Previous Studies

The results are generally consistent with previous research that shows that digital banking ecosystems increasingly rely on platform-based business models and strategic partnerships between financial and non-financial institutions (Ghosh and Golder 2026). Similar to (Ryan and Mukherjee 2026), this study confirms that participation in digital ecosystems improves financial inclusion. It does so by increasing access to digital financial services. However, this study adds to previous research by showing that technological capabilities alone are not sufficient for successful ecosystem participation. Strong governance, strategic partnerships and customer trust are also important factors for ecosystem success. This finding supports the work of (Akyildirim *et al.* 2025), who focused primarily on regulatory issues. It also shows how governance, innovation and customer value creation work together. Furthermore, unlike previous conceptual studies that examined digital banking technologies in isolation, this study integrates various technological and organizational factors into a single framework. This framework explains how ecosystem participants work together to create sustainable competitive advantage.

Limitations and Future Research

This study has several limitations. First, the analysis uses secondary data mainly from academic publications and publicly available case studies. As a result, the proposed conceptual framework has not yet been tested with primary data collected from banking professionals or customers. Second, the selected case studies mainly focus on large international financial institutions with advanced digital capabilities. Therefore, the findings may not fully reflect the situation of smaller banks or institutions in developing countries. Third, digital financial ecosystems continue to change rapidly. New technologies and regulatory developments may affect ecosystem structures beyond the scope of this study. Future research should test the proposed framework using expert surveys, Delphi studies, structural equation modeling or multiple case study analysis. Comparative studies between developed and developing countries may provide a better understanding of ecosystem maturity and institutional differences. Longitudinal studies can also examine how banking ecosystems change over time. They can examine how ecosystem participation affects bank performance, customer satisfaction and financial stability.

CONCLUSION

This study examined the transformation of banking services in the digital financial ecosystem. It demonstrated the significant impact of digital technologies and platform-based models on the banking sector. The findings show that banking is moving from a product and institution centric model to a customer and ecosystem centric approach. Technologies such as artificial intelligence, blockchain, cloud computing and open banking APIs are playing an important role in this transformation. In addition, ecosystem-based banking offers many advantages. These include better customer service, higher profitability, broader financial inclusion and faster innovation. However, these advantages are accompanied by major challenges, including security risks, data protection issues, regulatory complexity and stronger competition from technology companies.

From a theoretical perspective, this study contributes to existing research by providing a comprehensive analytical framework for the digital financial ecosystem. It combines ideas from platform theory, diffusion of innovation and dynamic capabilities theory. The study also extends previous research by emphasizing the strategic role of banks. It highlights the importance of collaboration and technological adaptation in a connected environment involving multiple participants. From a practical perspective, this study provides banks and regulators with useful strategies for digitalization, ecosystem participation and effective governance. It also offers concrete recommendations. Future research should continue to examine the long-term impacts of banking ecosystems on financial stability, competition and customer behavior. More research is also needed on the development of digital financial ecosystems in developing countries. Further research should examine the regulatory frameworks needed to balance innovation and risk management. Such research will be essential for improving academic knowledge and supporting practical applications in a continuously changing digital environment.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Mapping Research Trends in Circular Economy and Logistics: A Bibliometric Analysis Based on Web of Science

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ABSTRACT The purpose of this study is to determine the direction of the literature's development and to identify trends in scholarly publications in the fields of logistics and circular economy. The PRISMA framework was used in the systematic review procedure. The Web of Science database was thoroughly searched using the "All Fields" option and the query "circular economy" AND "logistics," covering all years and indexes. A total of 1784 publications were initially acquired. Following the screening process, 1771 papers from 2004 to 2026 were incorporated into the final study. Bibliometric analytic techniques were employed in the study, and bibliometric networks were visualised using VOSviewer software. The most productive and referenced scholars and nations were identified by analysing the distribution of publications across Web of Science categories, years, and types. Keyword structures were also assessed. The results offer a framework for directing further studies in this area.

KEYWORDS
Circular economy
Logistics
Bibliometric analysis

INTRODUCTION

The old linear economic model, predicated on the "take-make-dispose" strategy, is no longer as valid as it once was due to growing awareness of resource limits. The need to minimise resource waste necessitates more conscious use and consumption of resources both now and in the future, making the transition to circular economy principles inevitable (Ji-Hyland *et al.* 2025). The circular economy is based on a closed-loop supply chain approach aimed at increasing resource efficiency and improving environmental performance (Masudin *et al.* 2025). It also encompasses the restructuring of production and logistics processes and the effective management of supply chains (Makarova *et al.* 2018). In this respect, it is directly related to logistics and supply chain management (Ding *et al.* 2023). Indeed, it is stated that logistics processes and supply chain design play a critical role in the success of circular economy practices (Gonbadi *et al.* 2021).

A review of the literature revealed that, to the best of our knowledge, no study directly examined the intersection of circular economy and logistics from a bibliometric perspective. In contrast, existing bibliometric studies largely focus on circular economy and sustainable supply chain management or circular supply chain issues. In this respect, the present study systematically maps the literature at the intersection of circular economy and logistics, revealing research trends, collaboration networks, and prominent themes, thereby helping to fill this gap in the literature. In the study, bibliometric analysis, which has emerged as an effective method for revealing research trends in recent years, was preferred because traditional literature review methods are limited in scope and objectivity. In this way, the literature review has gained a more systematic and functional structure (Donthu *et al.* 2021). Various bibliometric techniques were applied to identify trends in the field (Garcilazo-López *et al.* 2026). Specifically, the study analysed the distribution of publications by Web of Science (WoS) categories, years, and types; identified the countries and researchers with the most publications and citations; and examined prominent keywords in the literature. Accordingly, the study aims to provide a comprehensive assessment of the current state of the literature and to guide future research.

This study is organised into six sections. After the introduction, the second section discusses the circular economy and logistics. The third section outlines the research methodology, while the fourth section presents the findings. The fifth section offers general evaluations and recommendations for future research. In the final section, the study's limitations are explained.

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CIRCULAR ECONOMY AND LOGISTICS

The circular economy is a concept based on industrial ecology and various other disciplines, and it is generally an approach that aims to protect natural capital, increase resource efficiency, and make systems restorative and regenerative by minimising waste (Garcilazo-López *et al.* 2026). The comprehensive use of a circular economy, based on the conservation of resources, climate, and the environment, helps to dispose of waste in a way that is both climate-friendly and environmentally sustainable, enabling the systematic removal of pollutants (Ji-Hyland *et al.* 2025). Unlike the linear economic model, this approach, contrary to the "take-make-discard" system, aims to keep resources in use for as long as possible, minimise waste, separate welfare from the consumption of virgin resources (Sauvé *et al.* 2016), and reintegrate resources into production processes at the end of their useful life (Garcilazo-López *et al.* 2026). Accordingly, the circular economy is defined as a holistic economic model that preserves the economic value of materials through recycling, reuse, and recovery processes, maximises the benefits derived from resources within technical and biological cycles, and makes production and consumption systems more sustainable (Neves and Marques 2022).

Today's business models must be restructured to simultaneously address economic, environmental, and social goals, and the circular economy plays a key role in this transformation (Butt *et al.* 2024). While the circular economy offers an industrial framework that reduces waste generation and promotes reuse oriented design by ensuring that products are reintroduced into the system at the end of their useful life, the effectiveness of this framework depends largely on the proper management of material and energy flows and on coordination among businesses (Valenzuela *et al.* 2021; Seroka-Stolka and Ociepa-Kubicka 2019). In this context, reverse logistics, green logistics, and ecological logistics are highlighted as some of the fundamental building blocks of the circular economy, particularly through closed-loop supply chains (Genovese *et al.* 2017; Theeraworawit *et al.* 2022; Mallick *et al.* 2023). Reverse logistics, encompassing the processes of collecting, recycling, and reintegrating used products into the system, reduces resource losses and, working in conjunction with forward logistics, ensures that waste streams are redirected back into production processes (Rogers and Tibben-Lembke 2001; Ding *et al.* 2023; Zhang *et al.* 2021). This contributes to both reducing environmental impacts and lowering the carbon footprint by increasing resource efficiency (Wang *et al.* 2019; Butt *et al.* 2024). Therefore, while the circular economy provides a strategic framework focused on resource conservation and waste prevention, reverse logistics transforms these goals into actionable recycling and recovery processes (Ji-Hyland *et al.* 2025).

Green logistics is defined as a comprehensive set of supply chain practices and strategies encompassing material management, waste reduction, packaging methods, and transportation activities, aimed at minimising the environmental impact and energy consumption arising from product distribution processes (Seroka-Stolka and Ociepa-Kubicka 2019). Therefore, when green logistics, which focuses on minimising emissions and optimising transportation and storage, is combined with the circular economy, these practices allow for more efficient logistics operations, further enhancing sustainability outcomes (Masudin *et al.* 2025). Ecological logistics is considered a subsystem that manages the collection, transportation, and recycling of waste in a way that minimises environmental impact (Seroka-Stolka and Ociepa-Kubicka 2019). Taken together, these logistics approaches emerge as fundamental elements supporting the closed-loop structure of the circular economy and make significant contributions to the development of sustainable supply chain management (Geissdoerfer *et al.* 2017; Nascimento *et al.* 2019).

MATERIALS AND METHODS

Bibliometric Analysis

Bibliometric analysis is a method that enables the systematic examination and evaluation of large-scale scientific data and has become increasingly common in recent years (Oztürk *et al.* 2024). This approach has gained importance, particularly because of its ability to effectively analyse large volumes of academic data and reveal research trends, and the limitations of traditional literature review methods in terms of scope and objectivity have made bibliometric analysis a more functional alternative (Donthu *et al.* 2021). In bibliometric analyses, databases like Scopus and WoS provide extensive data access, while software such as Gephi, Leximancer, and VOSviewer facilitate the analysis and visualisation of the obtained data (Donthu *et al.* 2021; Lim *et al.* 2024). This allows for a more holistic evaluation of the literature spanning many years. Researchers use bibliometric methods to evaluate the performance of publications and journals, analyse collaboration networks, examine the structure of scientific fields, and identify research trends (Donthu *et al.* 2021). In addition, this method helps identify gaps in the literature, develop new research topics, and contextualise studies (Yörük *et al.* 2024).

Data and Analysis

The methodological approach used in this study is based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which ensures transparency and systematicity in the selection of data sources and the analysis process (Moher *et al.* 2010; Akar *et al.* 2024). The PRISMA flowchart is presented in Figure 1 However, the WoS database was preferred for this study. WoS's selective indexing policy, which contains publications that adhere to strict worldwide academic quality standards, its standardised bibliographic record structure, and its reputation as a trustworthy data source frequently utilised in bibliometric analysis are important factors in the decision (Fang *et al.* 2018; Yan and Zhiping 2023; Oztemiz 2024; Altıntop 2025; Wan Mustapa *et al.* 2025; Lau *et al.* 2026; Taner and Kahveci 2026). Furthermore, the ability to export WoS data in a format compatible with bibliometric analysis software and the technical infrastructure supporting the analysis process were also influential factors in choosing this database. Additionally, combining records from other databases such as Dimensions and Scopus can raise the risk of methodological issues during the data merging process, like duplicate records and bibliographic discrepancies (Taner and Kahveci 2026). Therefore, the analysis was restricted to the WoS database alone in order to preserve methodological consistency in the study. However, the exclusion of some relevant publications indexed in other databases such as Scopus or Dimensions should be considered a limitation of the study. The protocol followed during the creation of the dataset is listed below:

· Identification time: April 16, 2026

· Database: WoS

· Search query expression: ("circular economy" AND "logistics"), "All Fields"

· Inclusion criteria: Peer-reviewed articles, proceedings papers, review articles, early access publications, book chapters

· Exclusion criteria: Corrections, editorial content, publications raising concerns, and retractions

· Sampling time constraint: 2004-April 16, 2026

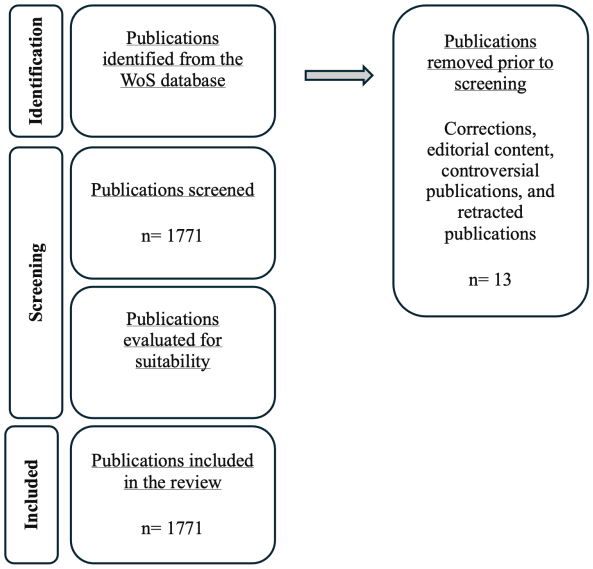

Figure 1 The PRISMA Flowchart

On April 16, 2026, a search was conducted in the WoS database using the "All Fields" option with the search query ("circular economy" AND "logistics"). All years and all WoS indexes were included in the filtering process. In this context, a total of 1784 publications were identified, including articles, proceedings papers, review articles, early access publications, book chapters, corrections, editorial materials, publications with expressions of concern, and retracted publications, all published between 1999 and 2026 (through April 16). However, during the analysis process, corrections, editorial content, publications raising concerns, and retractions were excluded. Ultimately, 1771 studies published between 2004 and 2026 were included in the sample. The dataset created in this process was made more reliable and suitable for analysis.

During the analysis process, VOSviewer (version 1.6.20) software was used to visualise bibliometric networks and analyse relational data. This tool offers collaborative, web based methods that cover basic types of analysis, such as co-occurrence, bibliographic matching, co-citation, and co-authorship (Boni *et al.* 2026; Garcilazo-López *et al.* 2026). VOSviewer's visualisation, mapping, and multidimensional analysis features, which enable detailed examination of datasets, have been key factors in its selection. In addition, thanks to its user friendly interface, VOSviewer enables researchers to more easily identify relationships and developmental trends in the literature (Dirik *et al.* 2023).

Within the studies examined, various techniques were employed in bibliometric analyses to identify the field's structural characteristics and trends (Garcilazo-López *et al.* 2026). In this context, the distribution of publications by WoS categories, publication years, and types was examined, the countries and researchers that produced the most publications and received the most citations were identified, and the keywords that stand out in the literature were analysed. In all network analyses, the Full Counting method was preferred, and the Association Strength normalisation method was used. Clustering operations were performed based on VOSviewer's default clustering algorithm and default parameters. The threshold values used in the analyses are explained under the relevant analysis headings.

FINDINGS

Table 1 shows the distribution of the publications examined in this study according to WoS categories. According to Table 1, the studies are primarily grouped under the fields of Environmental Sciences and Green Sustainable Science Technology. However, it is also noteworthy that significant research has been conducted in environmental, industrial, and manufacturing engineering. Table 2 shows the distribution of the studies examined by year.

Table 1 WoS Categories of the Studies Reviewed

WoS Categories	Number of Studies	%
Environmental Sciences	535	13.60
Green Sustainable Science Technology	505	12.84
Operations Research Management Science	346	8.80
Management	335	8.52
Environmental Studies	295	7.50
Engineering Environmental	248	6.31
Engineering Industrial	246	6.25
Engineering Manufacturing	196	4.98
Business	156	3.97
Computer Science Interdisciplinary Applications	115	2.92

Note: The top 10 categories with the most publications are listed. A publication may appear in more than one category.

Table 2 Distribution of the Studies by Year

Publication Year	Number of Studies	Publication Year	Number of Studies
2026	125	2015	8
2025	367	2014	5
2024	263	2013	5
2023	236	2012	4
2022	250	2011	3
2021	187	2010	8
2020	124	2009	4
2019	93	2008	9
2018	58	2007	7
2017	15	2006	3
2016	9	2004	1

According to Table 2, WoS publications in the field in question were published between 2004 and 2026. It is also evident that the number of publications has increased in recent years. Of these studies, 1218 are articles, 314 are proceedings papers, 244 are review articles, 72 are early access, 21 are book chapters, and 13 are other types. Figure 2 shows a distribution of the compiled publications by type.

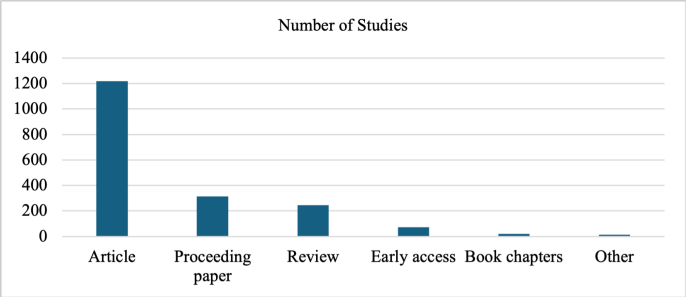

Figure 2 Distribution of studies by type

As shown in Figure 2, the vast majority of studies are journal articles. On the other hand, it is noteworthy that the number of conference papers, review articles, and, in particular, book chapters is quite limited.

Co-author Analysis

Based on a co-authorship analysis, a network map was created using the criteria of at least 1 publication and at least 1 citation to identify the most linked and collaborative authors. According to the authors with the most links, there are 547 authors grouped into 35 clusters, totalling 1559 links.

Table 3 Most Productive and Most Cited Authors

Author	Studies	Author	Citations
Joseph Sarkis	12	Joseph Sarkis	1683
Kannan Govindan	12	Abraham Zhang	1431
Borja Ponte	11	Yigit Kazancoğlu	1128
Yigit Kazancoğlu	10	Mahtab Kouhizadeh	1005
Patricia Guarnieri	10	Stefan Gold	996
Sunil Luthra	9	Pasquale Del Vecchio	994
Sachin Kumar Mangla	9	Steve Evans	972
Anil Kumar	8	Donald Huisingh	970
Abraham Zhang	8	Ana B. Lopes de Sousa Jabbour	970
Javier Puente	8	Piera Centobelli / Roberto Cerchione	959

Note: The top 10 most cited authors are listed.

Table 3 lists the top 10 most cited authors. According to the table, Joseph Sarkis and Kannan Govindan were identified as the authors with the most publications in the field, each with 12. Borja Ponte (11 publications), Yigit Kazancoğlu (10 publications), and Patricia Guarnieri (10 publications) are among the researchers with the most publications. In terms of citation numbers, Joseph Sarkis, Abraham Zhang, and Yigit Kazancoğlu stand out as the top three most cited authors. Figure 3, shows the co-authorship links and a graph illustrating the changes over the years.

When evaluated by colour distribution (Figure 3), the purple tones (2020–2021) indicate that some early stage studies were conducted through scattered collaborations. In contrast, the green tones (around 2022–2023) indicate a marked increase in collaborations during this period, while the yellow tones (2024–2025) are primarily observed in newly formed small clusters, revealing that the field is still expanding and that new researchers are joining the network.

Citation Analysis by Country

Geographic mapping represents the spatial distribution of research productivity across countries and institutions (Garcilazo-López *et al.* 2026). As part of this study, an analysis was conducted on 83 observation units linked to one another, based on the criteria that a country must have published at least 1 paper and received at least 1 citation, in order to create a network map of citations received by studies in the fields of the circular economy and logistics, categorised by their countries of origin. 18 clusters and 8809 total link strength were identified. Table 4 shows the number of citations and publications by country.

Table 4 Number of Citations and Publications by Country

Country	Studies	Citations
China	259	8756
United Kingdom	205	12314
India	201	7663
Italy	156	5937
United States	150	7895
Brazil	137	5543
Germany	118	5264
Spain	103	2758
Australia	93	4299
France	83	5660

Note: The top 10 countries with the highest number of published articles are listed.

Among the countries with the most publications are China (259 publications), the United Kingdom (205 publications) and India (201 publications); among the countries with the most citations are the United Kingdom (12314 citations), China (8756 citations), the United States (7895 citations), India (7663 citations) and Italy (5937 citations). Turkey ranks 16th in the number of publications (46) and 14th in citations (1847). Citation networks illustrating the citation analysis of countries and changes over the years are shown in Figure 4.

When Figure 4 is evaluated primarily in terms of colour distribution, the fact that purple tones (2021) appear in more limited areas indicates that the citation network was narrower in the early period. In contrast, the green tones concentrated at the centre of the network (particularly during the 2022–2023 period) are striking. This situation indicates that citations between countries increased significantly during those years and that scientific interaction intensified. On the other hand, the fact that yellow tones (2024) are more observed across the network and on new links indicates that new countries have recently been added to the network and

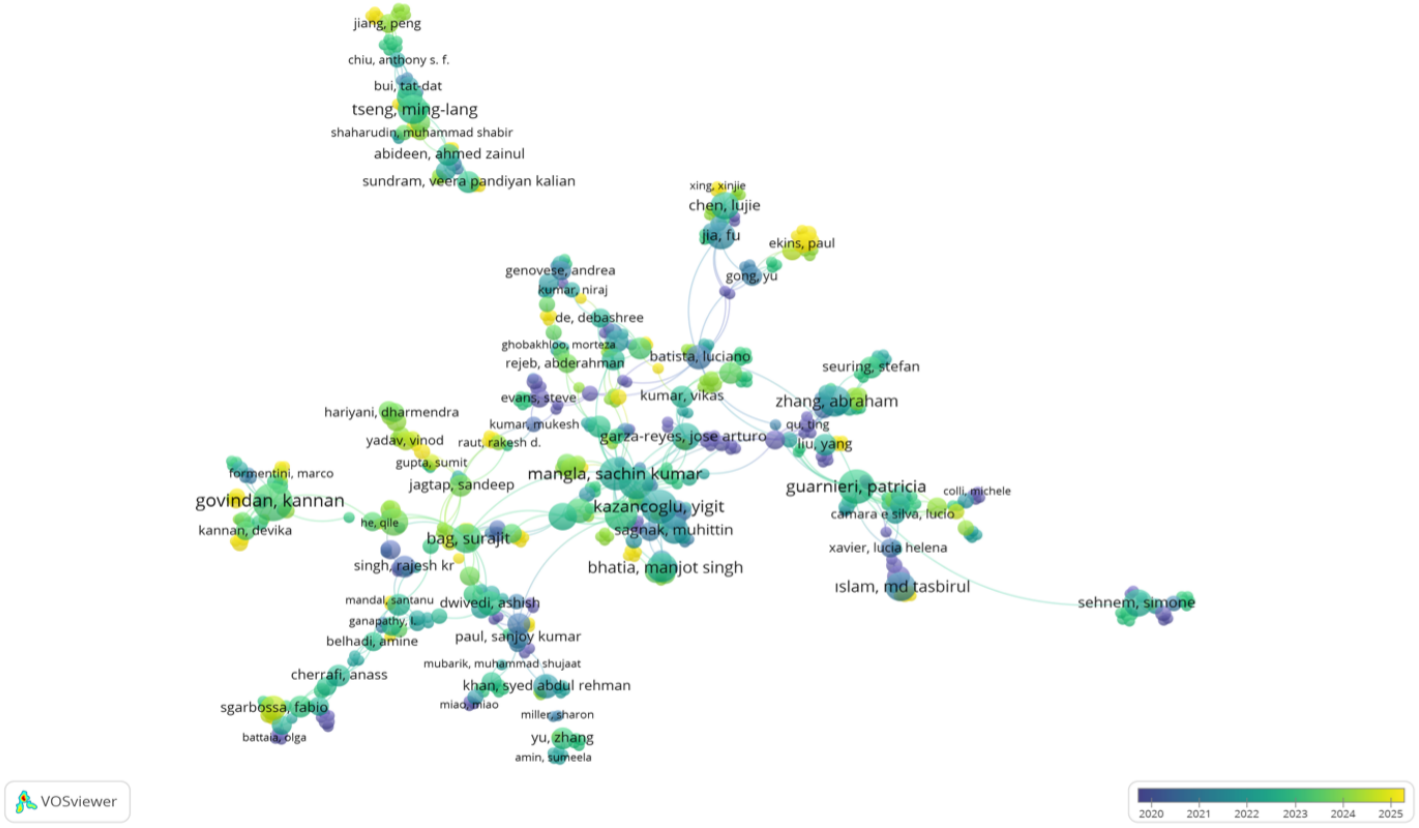

Figure 3 Co-author links and densities by year

that citation relationships continue to expand. In terms of density, the network has a distinct core structure, particularly comprising countries such as the USA, the UK, China, India, and Brazil. The fact that these countries are represented by larger nodes and have numerous connections indicates their central position in the citation network. In contrast, countries located farther from the centre of the network and represented by smaller nodes have a limited number of connections.

Keywords Analysis

Keyword analysis identifies the most common terms by analysing the keywords authors include in their works, providing insight into the most frequently researched topics and the evolution of the relevant field (Donthu *et al.* 2021; Garcilazo-López *et al.* 2026). In the present study, the minimum number of repetitions for a keyword was set at 5. The analysis, conducted on 179 observation units, identified 13 clusters and 5448 total link strengths. The most frequently occurring keywords are shown in Table 5.

As shown in Table 5, the terms "circular economy," "sustainability," "reverse logistics," "supply chain management" and "closed-loop supply chain" are the keywords most frequently used by researchers in their publications. These terms form the core of the relevant literature and are the keywords most frequently linked to other terms. Keyword links and the density of word usage by year are shown in Figure 5.

When Figure 5 is examined in terms of colour distribution, it is thought that the purple tones (2021), representing the early period, indicate that there was initially a focus on more specific topics. In contrast, the concept of circular economy, which is at the centre of the network, is predominantly concentrated in green tones and has become significantly prominent in the literature, especially in the 2022–2023 period, with studies concentrating around this axis.The fact that shades of yellow (2024) are seen more frequently in terms such as machine learning, recycling, and sustainable management indicates that new technologies and application focused initiatives have been on the rise recently.

When evaluated by density, the circular economy is by far the largest and most central node in the network. This indicates that the concept is a central theme in the literature and has strong

Table 5 Most Frequently Repeated Keywords

Keyword	Number of Repetitions
Circular Economy	1035
Sustainability	314
Reverse Logistics	287
Supply Chain Management	175
Closed-Loop Supply Chain	169
Industry 4.0	103
Recycling	79
Remanufacturing	78
Waste Management	71
Sustainable Development	63

Note: The top 10 most frequently occurring keywords are listed.

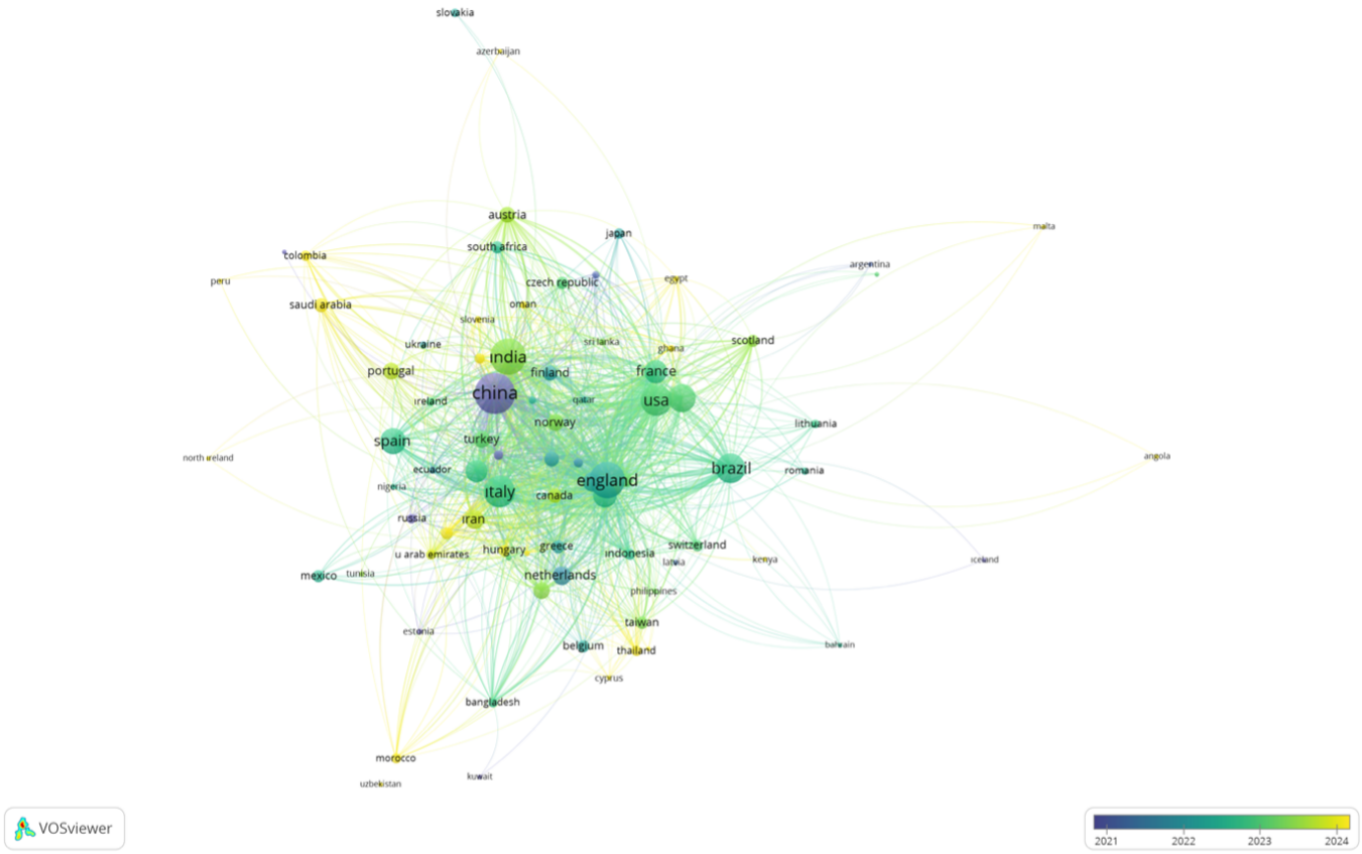

Figure 4 Country-Citation Links and Their Densities by Year

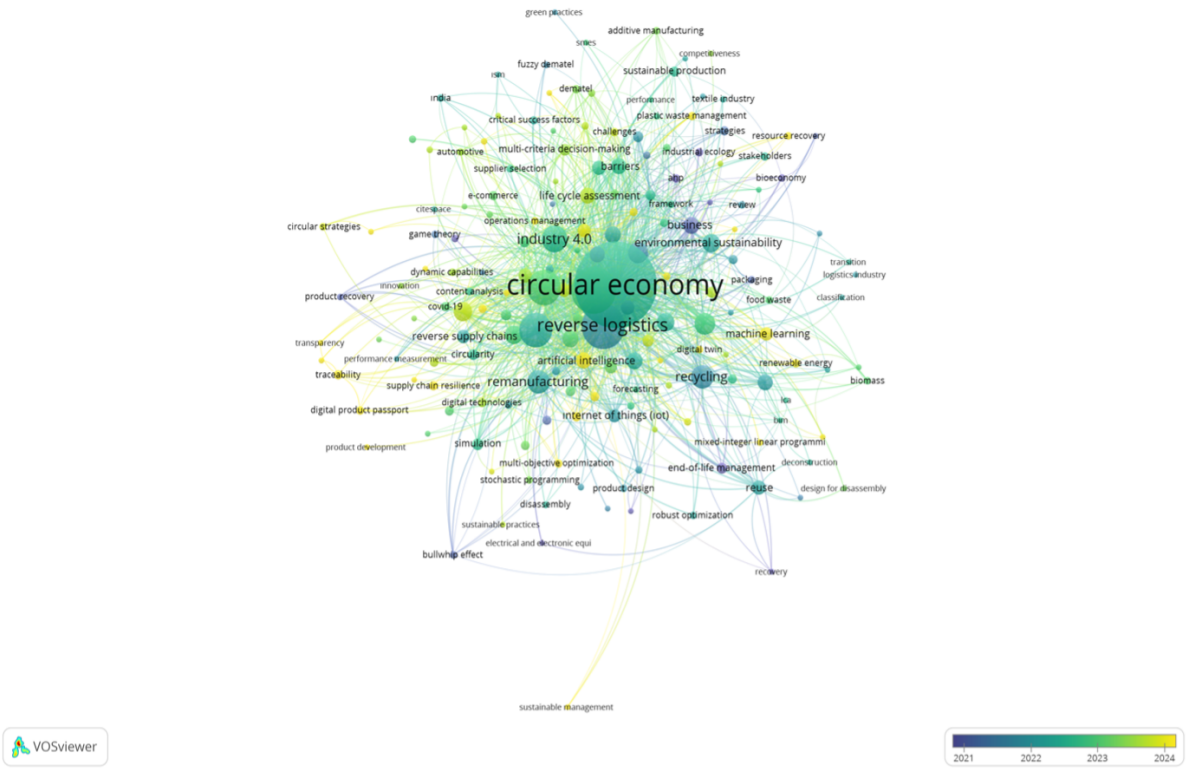

Figure 5 Most Frequently Used Keyword Links and Their Density by Year

links to other keywords. In addition, the fact that concepts such as reverse logistics, recycling, remanufacturing, and Industry 4.0 are represented by relatively large nodes demonstrates that these topics are among the fundamental components of the circular economy literature. Furthermore, the identification of links between the relevant field and keywords such as environment, digital transformation, and sustainability indicates interdisciplinary interaction.

CONCLUSION

In this study, which aimed to review publications in the fields of the circular economy and logistics and to identify development trends, a methodological approach based on the PRISMA framework was adopted to ensure transparency and systematicity in selecting data sources and conducting the analysis. In this context, bibliometric analysis techniques were used to identify the field's structural characteristics and trends. VOSviewer software was used to visualise bibliometric networks and analyse relational data. The findings are summarised below.

In the distribution of the publications by WoS categories, the field of Environmental Sciences accounts for the largest share. When examining the distribution of publications by year, an overall upward trend is evident, with the highest number in 2025. By publication type, articles make up the vast majority of studies. The author's analyses reveal that Joseph Sarkis and Kannan Govindan are the researchers with the most publications in the field. In addition, it has been determined that Joseph Sarkis is also the most cited author. An analysis of the temporal evolution of co-authorship networks reveals that early period studies featured more dispersed collaborations, whereas collaborations increased significantly between 2021 and 2024, with smaller, new clusters emerging after 2024. In country based analyses, China had the most publications, while the United Kingdom had the most citations. When evaluated in terms of country citation relationships and network density, it is evident that the United States, the United Kingdom, China, India, and Brazil form a strong core at the centre of the network.

According to the keyword analysis, the three most frequently used terms are "circular economy", "sustainability" and "reverse logistics". In particular, it was determined that the concept of the "circular economy" is the most dominant node in terms of both frequency of use and centrality within the network. However, the strong links between different keywords indicate that the field has an interdisciplinary structure. The findings present important implications for future studies. In particular, the small clusters that have emerged in recent years among co-authors are increasing collaboration opportunities for new researchers. At the same time, the identification of links between the circular economy, logistics, and other concepts, along with the recent increase in research on new technologies and applications such as machine learning, highlights significant potential for interdisciplinary research.

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Ethical standard

The author has no relevant financial or non-financial interests to disclose.

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Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The author declare that there is no conflict of interest regarding the publication of this paper.

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Analysis of the Application of IAS 2 Inventories in Financial Reporting

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ABSTRACT The primary objective of this article is to examine the theoretical framework and practical implementation principles of inventories within the scope of Turkish Accounting Standard TAS2. As one of the most dynamic components of current assets, inventories play a vital role in determining a firm's profit–loss structure and conducting liquidity analysis. This study adopts a descriptive and analytical methodology and is approached from a perspective consistent with International Financial Reporting Standards (IAS/IFRS). The findings indicate that valuing inventories at the lower of cost and net realizable value is critically important in preventing the overstatement of assets in accordance with the prudence principle. In addition, the allocation of production costs and their impact on operating profit are analyzed in depth. The study evaluates the FIFO and Weighted Average Cost methods, particularly with regard to their effects on financial statements in inflationary environments. The results demonstrate that the careful determination of net realizable value at the end of each reporting periods serves as a mechanism to prevent the deferral of unrealized losses to future periods. Ultimately, the accurate and comprehensive application of IAS 2 standards not only enhances the transparency of financial statements but also strengthens the international comparability of financial information.

KEYWORDS
IAS 2
Inventories
Net realizable value
Cost methods
Financial reporting transparency

INTRODUCTION

The IAS 2 (Inventories Standard), which constitutes a pivotal component of the Turkish Accounting Standards, regulates the accounting principles related to inventories, which are considered among the most vital assets of enterprises. The primary objective of this standard is to clarify the determination of inventory costs, ensure their accurate presentation in financial statements, and regulate issues such as inventory write-downs at the end of the reporting period. Within the scope of this study, the IAS 2: Inventories Standard, published by the Turkish Accounting Standards Board on January 15, 2005, is comprehensively analyzed. The regulation was issued under the authority and responsibility of the Turkish Accounting Standards Board and entered into force as a legal requirement for accounting periods beginning on or after December 31, 2005. Furthermore, the standard has been revised in line with evolving financial reporting requirements through various supplementary regulations enacted over time (Boydas Hazar 2020).

Following these updates, IAS 2 consists of a total of 40 articles organized into several major sections that collectively establish the principles for inventory accounting. Article 1 outlines the objective and underlying philosophy of the standard, while Articles 2–5 define its scope and field of application. Articles 6–8 present the key definitions and conceptual framework, followed by Article 9, which introduces the principles of inventory valuation. Articles 10–20 describe the composition of inventory costs, including purchase costs, conversion costs, other cost components, inventory costing for service providers, and products derived from agricultural activities. Articles 21–22 explain the techniques used for cost measurement, whereas Articles 23–27 specify the inventory cost formulas, such as the FIFO and weighted average methods. Articles 28–33 address the determination of net realizable value and inventory impairment, while Articles 34–35 explain the recognition of inventories as an expense. Finally, Articles 36–39 set out the disclosure requirements for financial statements and accompanying notes, and Article 40 specifies the effective date of the standard.

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While the IAS 2 Standard primarily concerns the asset structure of commercial enterprises from a financial accounting perspective, it also functions as an operational guideline for enterprises engaged in the production of goods or the provision of services within the framework of cost accounting. In this respect, the standard represents an indispensable cornerstone for ensuring transparency and comparability in financial reporting. Although IAS 2 generally covers all inventory items, certain assets are excluded due to their specific characteristics and alternative valuation requirements. In this context, financial instruments within the scope of IAS 32 and IFRS 9, as well as agricultural produce at the point of harvest regulated under IAS 41 Agriculture, fall outside the remit of this standard (Akgün 2012).

Pursuant to the standard, assets possessing the following characteristics are defined as inventories and evaluated within the scope of IAS 2:

- Commercial Goods: Assets purchased for resale and intended to be presented to customers without any further processing.
- Work-in-Progress: Assets that are not yet completed and remain in the production process at the reporting date.
- Raw Materials and Supplies: Materials held in enterprise warehouses for use in production or for consumption in the provision of services.

For enterprises operating in the service sector, inventory costs include all costs incurred up to the completion of the service. In particular, wages paid to personnel who are directly involved in the production or provision of services are classified as direct production costs. Conversely, expenses related to general administrative personnel that do not have a direct connection with production activities are excluded from inventory costs and are recognized directly as period expenses (Korga and Aslanoğlu 2024).

Two critical concepts are particularly significant in the year-end valuation of inventories:

- Net Realizable Value: The estimated selling price in the ordinary course of business, less the estimated costs of completion and the estimated costs necessary to make the sale.
- Fair Value: The amount for which an asset could be exchanged between knowledgeable and willing parties in an arm's length transaction under market conditions.

According to IAS 2, inventories must be measured at the lower of cost and net realizable value. This valuation approach is consistent with the principle of conservatism and aims to prevent the overstatement of assets in financial statements.

LITERATURE REVIEW

The findings related to listed companies indicate that, although the level of compliance with the disclosure requirements of IAS 2 is generally satisfactory, significant information gaps still exist in areas such as the reversal of inventory write-downs and the disclosure of pledged inventories. Moreover, the results demonstrate that firm size and the type of audit firm, particularly large international audit firms have a direct and positive impact on the quality of inventory-related disclosures (Polachová 2019). Morshed and Ramadan (2023) conclude that IAS 2 functions as a safeguard or filtering mechanism that prevents the inclusion of inappropriate cost items such as marketing expenses or costs arising from inefficiencies into the cost of inventories reported on the balance sheet. This approach ensures that the value of a company's assets is not overstated in annual financial reports.

Ferreira and Viana (2010) employed a case study method and comparative statistical analysis to examine the financial statements of companies listed on Euronext Lisbon. They concluded that the transition to international accounting standards resulted in statistically significant changes in inventory valuation. The authors found that the elimination of the LIFO method in accordance with the requirements of IAS 2 led to an increase in the book value of inventories reported on the balance sheet, thereby enhancing the quality and comparability of financial information. Their findings further indicate that by restricting the types of expenditures eligible for inclusion in inventory cost, the standard prevents artificial inflation of asset values and improves reporting transparency. Ultimately, the study demonstrates that compliance with IAS 2 provides a more realistic representation of corporate profitability and the status of current assets compared to the previously applied local standards. Öztürk (2017) employed comparative analysis and library-based research methods to examine differences in the measurement and accounting of inventories within the framework of Turkish tax legislation (VUK), national and international accounting standards (IAS/IFRS), and draft standards developed for small and medium-sized enterprises. He concluded that significant gaps exist between tax regulations and accounting standards regarding the calculation of inventory cost and related ancillary expenses, necessitating corrective adjustments. His findings indicate that modern standards, by emphasizing fair value and net realizable value, provide a more accurate representation of current assets. Ultimately, Öztürk emphasized the need to harmonize reporting practices in order to reduce accounting complexity within economic entities.

Kaya (2018) employed content analysis to compare Turkish Accounting Standard TMS 2 and the Financial Reporting Standard for Large and Medium-Sized Enterprises (BOBİ FRS) with respect to inventory accounting. She concluded that although the two sets of standards are largely compatible, notable differences exist in the determination of inventory cost and, in particular, in the recognition of revenues related to service-oriented entities. Her findings indicated that the majority of provisions concerning the measurement and reporting of inventories are aligned across both standards, and that the differences are mainly confined to specific technical details. Ultimately, Kaya emphasized the importance for auditors to clearly understand these distinctions in order to prepare accurate financial reports that comply with the applicable standards. Sellhorn and Gornik-Tomaszewski (2006) employed qualitative analysis and a comprehensive review of the research literature to examine the implications of International Accounting Standards (IAS) regulations on cross-country differences in accounting systems. They concluded that although the mandatory adoption of these standards within the European Union led to apparent convergence, institutional and national differences continued to influence the quality of financial reporting. Their findings suggested that researchers should move beyond a sole focus on formal rules and pay greater attention to environmental characteristics and managerial incentives that shape the implementation of these standards. Özyapıcı (2019) employed a case study methodology to examine the impact of Turkish Accounting Standard TMS 2 (equivalent to IAS 2) on the analysis of idle capacity and the management of production costs. He concluded that by requiring fixed production overheads to be allocated on the basis of normal capacity, this standard enables a clear distinction between actual idle capacity and unavoidable idle capacity in managerial reports. His findings indicated that this approach prevents inefficiency-related costs from being transferred to product cost and provides

managers with a critical tool for strategic decision-making in cost control.

PRINCIPLES OF INVENTORY VALUATION

The fundamental philosophy underlying IAS 2 Inventories is based on the principle of prudence. Accordingly, inventories should not be presented in the financial statements at amounts exceeding the economic benefits expected to be realized from their sale. The standard seeks to enhance the reliability and faithful representation of financial statements by preventing the overstatement of assets. In line with the prudence nonce, IAS 2 requires inventories to be measured at the lower of cost and net realizable value. Net realizable value is defined as the estimated selling price in the ordinary course of business less the estimated costs of completion and the estimated costs necessary to make the sale (Sellhorn and Gornik-Tomaszewski 2006). To clarify the application of this principle, the following examples are presented:

Situation A: Assume that the cost of a product held in inventory is 40,000 TL. If the estimated selling price is 30,000 TL and the expected selling expenses amount to 4,000 TL, the net realizable value will be 26,000 TL (30,000 − 4,000). In accordance with the lower of cost and net realizable value rule, the inventory should be recognized in the financial statements at 26,000 TL.

Situation B: If the net realizable value of the same inventory item were higher than its cost, for example, 45,000 TL, the inventory would continue to be measured at its historical cost of 40,000 TL. Under IAS 2, unrealized increases in inventory value are not recognized as gains. Conversely, any decline in value is recognized immediately as an expense, ensuring that the financial statements present a true and fair view of the entity's financial position.

DETERMINATION OF INVENTORY COSTS

In accordance with IAS 2, the cost of inventories comprises all costs incurred in acquiring the inventories, converting them, and bringing them to their present location and condition. Inventory costs are generally classified into two main categories: purchase costs and conversion costs.

Purchase Costs

Purchase costs include expenditures directly attributable to the acquisition of finished goods, raw materials, and services. The components of purchase costs are as follows (Özyapıcı 2019).

- Purchase Price: The net price paid to acquire the inventory.
- Import Duties and Customs Charges: Mandatory costs incurred during the importation process.
- Transportation Costs: Expenses related to transporting inventories to the entity's premises.
- Loading, Unloading, and Handling Costs: Costs incurred during the physical movement and initial handling of inventories.
- Non-refundable Taxes: Taxes and duties that cannot be recovered from tax authorities.
- Trade Discounts and Rebates: These are deducted from the purchase price when determining the cost of inventories.

Conversion Costs

Conversion costs are incurred once inventories enter the production process and represent the costs necessary to transform raw materials into finished goods. These costs include:

- Direct Labor Costs: Wages and related costs of personnel directly involved in the production process.
- Production Overheads: Both fixed and variable indirect costs related to production activities, such as factory depreciation, maintenance, and energy expenses, which are systematically allocated to units of production.

Costs that do not contribute directly to bringing inventories to their present location and condition such as general administrative expenses are excluded from inventory cost and recognized as period expenses. Financing costs are also expend unless capitalization is permitted under the provisions of IAS 23 Borrowing Costs (Berli 2014).

INVENTORY COST MEASUREMENT METHODS

The IAS 2 standard permits specific cost measurement techniques that enable enterprises to determine inventory costs in a manner consistent with their operational structures and the nature of their inventories. Especially in complex production environments or in the retail sector where a large number of inventory items exist these techniques are applied to ensure that inventory costs are measured as faithfully as possible (Aygün 2014).

Standard Cost Method

The standard cost method is based on the principle of multiplying predetermined standard quantities by standard prices established prior to the commencement of production. Under this method, pre budgeted data relating to raw materials, direct labor, and manufacturing overheads are used to calculate inventory costs. According to IAS 2, the use of the standard cost method is permitted only if the resulting cost figures closely approximate actual costs. If significant variances arise between standard costs and actual costs, such differences must be analyzed and adjusted at the end of the accounting period.

Retail Method

In the retail sector such as supermarkets and apparel stores where inventories consist of numerous items with rapidly changing prices and relatively similar profit margins, determining the cost of each individual item may be impractical. In such cases, the retail method is applied (Yılmaz 2020). The retail method determines the cost of inventories by deducting an appropriate average gross profit margin from their sales value (tag price). Under this approach, the estimated cost of inventories is calculated by subtracting the average gross profit rate applicable to a specific product group from the total sales value of those inventories. This method provides a practical and efficient solution, particularly for large scale retail enterprises where detailed cost tracking and physical inventory counting are difficult to perform.

ALLOCATION OF INVENTORY COSTS AND COST FORMULAS

Since inventories constitute a significant portion of an enterprise's current assets, the accurate allocation and valuation of inventory costs are crucial for the reliability and integrity of financial statements. IAS 2 specifies several cost formulas that may be used to determine the flow of inventory costs and the valuation of ending inventories.

FIFO Method (First-In, First-Out)

The FIFO method is based on the assumption that inventories acquired first are sold first.

- Mechanism:
  Under the FIFO method, inventories remaining at the end of the accounting period are valued using the most recent acquisition costs.
- Analysis:
  In inflationary environments where purchase prices are rising the FIFO method generally results in higher gross profit and, consequently, a higher taxable income, as older inventories with lower costs are assigned to the cost of goods sold. At the same time, the ending inventory reported on the balance sheet reflects values that are closer to current market prices, thereby enhancing the relevance of financial information (White 2021).

Table 1 FIFO Method Practical Example

Date	Transaction	Qty. (Units)	Unit Price (TL)	Total (TL)	Description
01.01.2020	Receipt	1,000	55	55,000	Initial inventory batch
09.01.2020	Receipt	500	80	40,000	Second inventory batch
15.01.2020	Receipt	500	100	50,000	Third inventory batch
20.01.2020	Issue	500	55	27,500	FIFO: First in, first out (Jan. 1 stock)
25.01.2020	Receipt	500	100	50,000	New inventory receipt
30.01.2020	Issue	1,000	55–100	72,500	FIFO: 500 × 55, 250 × 80, 250 × 100

Source: Author's original work.

Issue of 01.01.2020: Pursuant to the FIFO method, the inventories first acquired are the first to be issued. Consequently, 500 units are issued from the 1,000 units of stock dated 01.01.2020.

Cost: 500 ×55 TL = 27,500 TL

Issue of 30.01.2020: The issuance is conducted from the remaining inventory. According to FIFO, the oldest stock is prioritized:

Remaining from 01.01.2020: 500 units × 55 TL = 27,500 TL

From 09.01.2020: 250 unit × 80 TL = 20,000 TL

From 25.01.2020: 250 units × 100 TL = 25,000 TL

Total Issue Cost: 72,500 TL

Remaining Inventory (as of 31.01.2020):

Inventory remaining from the final batch: 500 units from 25.01.2020 × 100 TL = 50,000 TL

LIFO Method (Last-In, First-Out) and the IAS 2 Prohibition

The LIFO method is based on the assumption that the most recently purchased inventories are the first to be sold.
Under this method, inventories remaining at the end of the accounting period are valued using the oldest historical costs. As a result, the cost of goods sold is reported at higher amounts, which leads to lower reported profit for the period.
It is important to note that the IAS 2 standard does not permit the use of the LIFO method. Due to its failure to adequately reflect the economic reality of an entity's financial position and its potential to facilitate profit manipulation, LIFO has been eliminated from the Turkish Accounting Standards in line with International Financial Reporting Standards (Tan 2020).

Practical Example

At Mavi Tekstil A.Ş., an issue of 500 units was performed on 20.01.2020. Had the LIFO (Last-In, First-Out) method been employed, 500 units would have been issued from the most recent batch of 750 units at 100 TL, resulting in a cost of 50,000 TL.

Table 2 Practical Example Regarding the FIFO Method

Date	Transaction	Qty. (Units)	Unit Price (TL)	Total (TL)	Description
20.01.2020	Issue	500	100	50,000	The most recent batch (100 TL) was utilized
30.01.2020	Issue	250	100	25,000	250 units remaining from the Jan. 25 receipt
30.01.2020	Issue	250	80	20,000	250 units from the Jan. 09 receipt
30.01.2020	Issue	500	55	27,500	500 units from the Jan. 01 receipt
Remaining	–	**500**	**55**	**27,500**	**Inventory remaining from the Jan. 01 receipt**

Source: Author's original work.

Table 3 Practical Example of the Weighted Average Cost Method

Date	Transaction	Quantity (Units)	Unit Price (TL)	Total (TL)
01.01.2020	Receipt	1,000	55	55,000
09.01.2020	Receipt	500	80	40,000
20.01.2020	Issue	500	?	?
25.01.2020	Receipt	500	100	50,000
30.01.2020	Issue	1,000	?	?

Source: Author's original work.

While issuing 1,000 units on 30.01.2020, 250 units (at 100 TL) from the 25.01 receipt are utilized first, followed by 250 units (at 80 TL) from the 09.01 receipt, and finally, 500 units (at 55 TL) from the 01.01 receipt. The total cost is determined to be 72,500 TL. The remaining inventory is calculated as 500 units from the 01.01 receipt 55 TL = 27,500 TL.

Weighted Average Cost Method

Under this method, a single unit cost is determined by calculating the weighted average of the cost of inventories at the beginning of the period and the costs of all inventories purchased during the same period. The weighted average cost method is considered one of the most appropriate and balanced approaches, particularly in situations where prices fluctuate frequently or where inventories consist of homogeneous and intermingled items. By smoothing cost variations over the period, this method helps reduce sharp fluctuations in reported profit or loss and provides a more stable cost structure.

The selection of an inventory cost calculation method is not merely an accounting procedure but also a strategic management decision. Inventory costs directly affect the cost of goods sold (COGS) and, consequently, influence net profit and the equity structure of the enterprise. While reporting higher profits may enhance an enterprise's credibility and investor confidence, it simultaneously results in higher corporate tax obligations. Therefore, enterprises are required to apply their chosen cost method consistently in accordance with IAS 2 and to disclose the selected method in the notes to the financial statements (Şahin and Koç 2020).

1. Calculation of Weighted Average Cost (Prior to the Issue on 20.01.2020)

- Total Cost: 55,000 + 40,000 = 95,000 TL
- Total Inventory: 1,000 + 500 = 1,500 units

- Weighted Average Cost: $\frac{95000}{1500}$ = 63.33TL/unit

Issue on 20.01.2020 (500 units):

- 500 x 63.33 = 31,665 TL

Remaining Inventory (Post-20.01):

- 1,500 - 500 = 1,000 units
- Remaining Cost: 1,000 x 63.33 = 63,330 TL

2. Weighted Average Cost Following New Receipt (25.01.2020)

- Remaining Inventory Cost + New Receipt: 63,330 + 50,000 = 113,330 TL
- Total Inventory: 1,000 + 500 = 1,500 units
- New Weighted Average Cost: $\frac{113330}{1500}$ =75.55 TL/unit

Issue on 30.01.2020 (1,000 units):

- 1,000 x 75.55 = 75,550 TL

Remaining Inventory (Post-30.01):

- 1,500 - 1,000 = 500 units
- Remaining Cost: 500 x 75.55 = 37,775 TL

Table 4 Practical Example Regarding the Weighted Average Cost Method

Date	Transaction	Quantity (Units)	Unit Price (TL)	Total (TL)
20.01.2020	Issue	500	63.33	31,665
25.01.2020	Receipt	500	100	50,000
30.01.2020	Issue	1,000	75.55	75,550
Remaining Inventory	–	**500**	**75.55**	**37,775**

Source: Author's original work.

IMPAIRMENT OF INVENTORIES AND ACCOUNTING PRINCIPLES

Following initial recognition, inventories may experience a decline in value due to various internal and external factors. Under IAS 2, presenting inventories in the financial statements at amounts exceeding their net realizable value is inconsistent with the principles of prudence and fair presentation. Therefore, inventories must be reviewed at the end of each reporting period to assess whether any impairment has occurred. The primary factors that may cause the net realizable value of inventories to fall below their cost are as follows (Santos *et al.* 2021).

- Physical Damage and Deterioration: Losses arising from breakage, spoilage, or expiration during the storage or transportation of inventories.
- Technological or Commercial Obsolescence: Situations in which products become outdated, unfashionable, or technologically obsolete, leading to a loss of market relevance.
- Decline in Selling Prices: Reductions in market selling prices below cost due to increased competition or a contraction in demand.
- Increase in Completion and Selling Costs: Unexpected increases in labor, material, or marketing expenses required to complete or sell the inventories.

Enterprises are required to assess their inventories at the end of each accounting period. If the net realizable value of an inventory item is lower than its cost, the difference must be recognized as an allowance for inventory impairment and recorded as an expense in the period's statement of profit or loss. Failing to recognize inventory impairment and reporting inventories at amounts higher than their recoverable value constitutes a misrepresentation of financial statements. Within the framework of financial reporting standards, such practices are regarded as irregularities whether arising from error or intentional manipulation. The misstatement of asset values misleads investors and creditors and ultimately undermines the credibility of the enterprise (Badem and Özbek 2013). If the conditions that gave rise to the impairment no longer exist for example, due to a subsequent recovery in selling prices the previously recognized impairment loss may be reversed, provided that the reversal does not exceed the amount of the original impairment loss. Such reversals are recognized as income in the relevant reporting period.

Practical Example

Aytek Ticaret A.Ş. is a commercial enterprise operating in Istanbul that procures goods from suppliers located in Bursa. During June, the company increased its capital, purchased commercial goods from Bursa, incurred transportation costs, and returned a portion of the goods that did not meet quality standards. In addition, a trade discount was obtained from the supplier. Subsequently, Aytek Ticaret A.Ş. sold part of its inventory to customers in Istanbul on credit. During this process, the company incurred transportation expenses related to sales, accepted customer returns, and granted additional sales discounts. At the end of the accounting period, calculations revealed that the company's ending inventory amounted to 85,000 TL, the cost of goods sold totaled 34,000 TL, net sales were 48,000 TL, and gross profit amounted to 14,000 TL.

List of All Transactions

Transaction 1 Capital Injection: Aytek enterprise has secured 550,000 TL in cash through the issuance of capital stock. Transaction 2 Purchase of Commercial Goods: Commercial goods amounting to 140,000 TL were purchased, with VAT (10%) totaling 14,000 TL. Half of the consideration was paid in cash, while the remaining half was purchased on credit. Transaction 2 Supplementary Transportation Expense: An obligation of 3,000 TL + 300 TL VAT was incurred for the transportation of the purchased goods. This expenditure is capitalized into the cost of the inventory.

Transaction 3 Returns to Supplier: Goods valued at 20,000 TL + 2,000 TL VAT were returned to the supplier due to quality discrepancies. Transaction 4 Return Shipping: 1,000 TL + 100 TL VAT was paid in cash for the transportation of the returned goods. Transaction 5 Supplier Discount Notification: The supplier provided a price reduction (discount) amounting to 5,000 TL + 500 TL VAT.

Transaction 6 Credit Sale: Goods with a cost of 40,000 TL were sold on credit for 60,000 TL + 6,000 TL VAT. Transaction 7 Transportation Expense Related to Sale: 2,000 TL + 200 TL VAT was paid in cash for the transportation costs of the sold goods. Transaction 8 Sales Returns: A customer returned goods valued at 9,000 TL + 900 TL VAT. The cost of these goods is 6,000 TL.

Transaction 9 Return Shipping: 1,000 TL + 100 TL VAT was paid in cash for the transportation of the returned goods back to the warehouse. Transaction 10 Sales Discount: A discount amounting to 3,000 TL + 300 TL VAT was granted to the customer.

Journal Entries (BCC Records) Aytek Enterprise

01.04.2024

100 CASH ACCOUNT DEBIT: 550,000.00
500 CAPITAL ACCOUNT CREDIT: 550,000.00
Description: Recording of cash capital injection through share issuance.

03.04.2024

153 COMMERCIAL GOODS ACCOUNT DEBIT: 140,000.00
191 DEDUCTIBLE VAT ACCOUNT DEBIT: 14,000.00
100 CASH ACCOUNT CREDIT: 77,000.00
320 SUPPLIERS ACCOUNT CREDIT: 77,000.00
Description: Purchase of commercial goods; 50% paid in cash and 50% on credit.

03.04.2024

153 COMMERCIAL GOODS ACCOUNT DEBIT: 3,000.00
191 DEDUCTIBLE VAT ACCOUNT DEBIT: 300.00
320 SUPPLIERS ACC CREDIT: 3,300.00
Description: Capitalization of inward transportation costs into the inventory cost.

05.04.2024

320 SUPPLIERS ACCOUNT DEBIT: 22,000.00
153 COMMERCIAL GOODS ACCOUNT CREDIT: 20,000.00
391 CALCULATED VAT ACCOUNT CREDIT: 2,000.00
Description: Return of defective goods to the supplier.

06.04.2024

760 MARKETING, SALES, AND DISTRIBUTION EXPENSES DEBIT: 1,000.00
191 DEDUCTIBLE VAT ACCOUNT | DEBIT: 100.00
100 CASH ACCOUNT CREDIT: 1,100.00
Description: Cash payment for outward transportation of returned goods (recognized as period expense).

08.04.2024

320 SUPPLIERS ACCOUNT DEBIT: 5,500.00
153 COMMERCIAL GOODS ACCOUNT CREDIT: 5,000.00
391 CALCULATED VAT ACCOUNT CREDIT: 500.00
Description: Recognition of trade discount granted by the supplier.

10.04.2024

120 BUYERS (ACCOUNTS RECEIVAB DEBIT: 66,000.00
600 DOMESTIC SALES ACCOUNT CREDIT: 60,000.00
391 CALCULATED VAT ACCOUNT CREDIT: 6,000.00
621 COST OF COMMERCIAL GOODS S DEBIT: 40,000.00
153 COMMERCIAL GOODS ACCOUNT CREDIT: 40,000.00
Description: Credit sale of goods and simultaneous recognition of cost of sales.

11.04.2024

760 MARKETING, SALES, AND DISTRIBUTION EXPENSES DEBIT: 2,000.00
191 DEDUCTIBLE VAT ACCOUNT DEBIT: 200.00
100 CASH ACCOUNT CREDIT: 2,200.00
Description: Cash payment for transportation costs related to sales.

15.04.2024

610 SALES RETURNS ACCOUNT DEBIT: 9,000.00
191 DEDUCTIBLE VAT ACCOUNT DEBIT: 900.00
120 BUYERS (ACCOUNTS RECEIVABLE) CREDIT: 9,900.00
153 COMMERCIAL GOODS ACCOUNT DEBIT: 6,000.00
621 COST OF COMMERCIAL GOODS SOLD CREDIT: 6,000.00
Description: Re-entry of returned goods into inventory and adjustment of cost of sales.

Table 5 Summary Table of Ledger Balances

Account Name	Total Debits	Total Credits	Balance (Ending)
153 Commercial Goods	150,000 TL	65,000 TL	85,000 TL (Debit Balance)
621 Cost of Goods Sold	40,000 TL	6,000 TL	34,000 TL (Net COGS)

Source: Author's original work.

Net Ending Inventory Value: 85,000 TL
Net Cost of Goods Sold (COGS): 34,000 TL

16.04.2024

760 MARKETING, SALES, AND DISTRIBUTION EXPENSES DEBIT: 1,000.00
191 DEDUCTIBLE VAT ACCOUNT DEBIT: 100.00
100 CASH ACCOUNT CREDIT: 1,100.00
Description: Payment for inward transportation of goods returned by customers.

20.04.2024

611 SALES DISCOUNTS ACCOUNT | DEBIT: 3,000.00
191 DEDUCTIBLE VAT ACCOUNT | DEBIT: 300.00
120 BUYERS (ACCOUNTS RECEIVABLE) | CREDIT: 3,300.00
Description: Post-sale discount granted to the customer.

Year-End Summary and Analysis (31.12.2024)

Inventory Account Summary (Account 153):

- Total Debits: 150,000.00 TL *(Purchases + Inward Freight + Returns In)*
- Total Credits: 65,000.00 TL *(Returns Out + Discounts + Cost of Sales)*
- Ending Inventory Balance: 85,000.00 TL

Net Cost of Goods Sold (Account 621):
Initial Cost Recognition: 40,000.00 TL (Debit)
Adjustment for Sales Returns: 6,000.00 TL (Credit)
Net Cost of Commercial Goods Sold: 34,000.00 TL

CONCLUSION

This study demonstrates that IAS 2 (Inventories) is not merely a collection of accounting rules but rather a strategic management framework that plays a vital role in safeguarding an enterprise's financial health and long-term sustainability. The findings indicate that effective inventory management, when conducted in accordance with IAS 2, contributes significantly to reducing financial risk and strengthening the overall financial structure of the entity. The results reveal that an enterprise's liquidity position is closely linked to the quality of its current assets, particularly inventories. The quality of these assets depends largely on whether inventories are managed, measured, and reported in compliance with IAS 2 criteria. The more consistently enterprises apply these standards, the more accurately they can anticipate future cash flows and manage liquidity risks. Such disciplined application enhances the firm's financial flexibility and its ability to respond to changing economic conditions.

The analysis further shows that IAS 2 functions as an effective decision-support tool for management by providing reliable and relevant information regarding production planning, sales strategies, and optimal inventory levels. Poorly managed inventories may result in resource shortages during operational disruptions, potentially bringing business activities to a standstill. In contrast, an inventory system aligned with IAS 2 helps prevent such bottlenecks and supports the continuity of operations. In conclusion, IAS 2 serves as a protective mechanism that shields enterprises not only from immediate financial losses but also from the risk of future insolvency and financial distress. To preserve financial integrity and ensure sustainable performance, enterprises must go beyond simple record-keeping and regularly conduct financial analyses based on accurate and IAS 2–compliant inventory information.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

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Design of a Mixed-Zone Completion Using a Single Oil Production Column in a Non-Eruptive Well with Two Oil and Gas Reservoirs

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ABSTRACT The objective of this paper was to design a multi-zone completion to produce oil from a well designated PX (for confidentiality reasons). The well contains two reservoirs: one with non-eruptive oil and the other with eruptive deep-seated gas reservoir. Analysis reveals that the initial hydrocarbon reserves in the oil and gas reservoirs indicate that R7 oil reservoir contains 4.517396985×10^{10} STB of initial oil, and the gas reservoir contains 29.04429927×10^{6} MMscf of initial gas. A multi-zone completion scheme is design to extract oil from the deep gas reservoir using a single production column. After implementing the proposed completion, the R7 oil reservoir produces oil at a rate of 2,700 STB/d, with production attributed to the deep-seated R8 gas reservoir. Three oil prices per barrel were selected based on market price fluctuations over a period of 10 year (Low: Scenario 1, Medium: Scenario 2, and high: Scenario 3). The economic evaluation of the completion reveals that Scenario 1 has an NPV (1) of $328,7843 and an IRR (1) of 16.63%, Scenario 2 has an NPV (2) of $602.4843 and an IRR (2) of 12.14%, and Scenario 3 has an NPV (3) of $687.1949 and an IRR (3) of 9.62%. The production of oil from the oil reservoir powered by the deep-well gas reservoir remains a profitable regardless of the price per barrel.

KEYWORDS
Hydrocarbon recovery
Oil and gas reservoirs
Non-eruptive
Multi-zone completion
Nodal analysis
Economic evaluation

INTRODUCTION

The efficient and economical exploitation of hydrocarbon reservoirs is a major challenge for the oil industry (Amyx 1960; Craft 1991; Seyyedattar *et al.* 2020). Conventional development strategies often involve the sequential exploitation of individual reservoirs, potentially leaving significant reserves unexploited due to technical or economic constraints (Wattenbarger and Economides 1993; Bradley 1987; Zheng *et al.* 2017). This limitation is particularly pronounced in mature fields, where it is becoming increasingly difficult to achieve marginal production gains (Khor *et al.* 2017; Miller and Sorrell 2014; Wang *et al.* 2023). This paper addresses the challenge of how to produce oil from one reservoir using gas from another, all within the same well. It examines the challenge of improving hydrocarbon recovery by analyzing the feasibility of simultaneous oil production. It is based on producing oil from a shallow reservoir and gas from a deep reservoir within the same well to improve hydrocarbon recovery by exploring the feasibility of simultaneously producing oil from a shallow reservoir and gas from a deep reservoir within the same well (Bera *et al.* 2024; Lyons 2016; Malozyomov *et al.* 2023). Such integrated production approaches offer the potential to improve the overall economics of the field and reduce environmental impact (Holditch 2006; Jiang *et al.* 2019; Ericson *et al.* 2019). More specifically, it studies an innovative completion strategy designed to enable the extraction of oil from the deep gas reservoir. It had previously been considered unreliable for oil production while leveraging existing well infrastructure and minimizing the need for costly drilling of new wells (Beggs 2003; Brown 1967; Holdaway 2014).

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The growing interest in minimizing costs and maximizing energy efficiency, exacerbated by market volatility and environmental concerns, highlights the urgency of developing innovative solutions (IEA 2022; Farghali *et al.* 2023; Lv 2023). This paper aims to develop and evaluate a technically and economically viable completion solution that enables oil production from deep gas reservoirs, thereby increasing overall hydrocarbon recovery and maximizing asset value (Lake 1989; Alvarado and Manrique 2010; Maryam *et al.* 2024). It draws on a comprehensive al review of the literature on advanced completion techniques, multiphase flow in wellbores, and the economic evaluation of oil projects, in order to propose an original and pragmatic approach to solving this complex problem (Guo 2017; Allen 2016; Brill 1987; Kay and Nedderman 1974; Epelle and Gerogiorgis 2020; Wan 2011). The economic analysis includes a sensitivity analysis to assess the impact of fluctuations in oil and gas prices on the project's profitability. This design takes into account the challenges associated with multiphase flow and incorporates inflow control devices to optimize performance and minimize the risk of production problems.

The research question addressed: How can a suitable completion design be developed that effectively harnesses the high pressure of the lower gas reservoir to enable optimal production of the heavy oil contained in the upper reservoir via a production string? The overall objective is to identify a completion design that allows for the production of oil from the deep gas reservoir. To accomplish the purpose of this paper, three specific objectives were established: to quantify the hydrocarbons in place (oil and gas); to propose a completion design for producing this oil from the deep gas reservoir; and to simulate this completion design and perform an economic evaluation. To achieve these objectives, this paper is organized into three sections. Section 1 presents the introduction to the paper. Section 2 presents the data, the software used, the methodology employed to achieve the set objectives, and the various results obtained. Finally, Section 3 presents the results and discussion. Finally, Section 4 concludes the paper by summarizing the main findings, discussing their implications, outlining the study's limitations, and providing recommendations for future research.

MATERIALS AND METHODS

A number of equipment and tools was utilised for the analysis of data, including software such as PROSPER V15.0 and Microsoft Excel, in addition to field equipment and measuring instruments that were adapted to the particular domains of this study. The data made available for this paper consist of two categories: geological data and reservoir data, for which these data were obtained from national geological surveys, international open-access repositories, and direct field or operational measurements. Key methods include utilizing public government databases, accessing academic or commercial subsurface archives, and gathering direct well data. As illustrated in Figure 1, the geological data has been extracted from the logging data of the PX well.

Figure 1 presents an excerpt from the logging data of well PX. Well PX was drilled in 1981 (started on February 24, 1981; completed on April 10, 1981), and the document was modified on December 3, 2005. Its total depth is 1871. For the logging data, the figure displays logging traces such as density (RHOB), porosity (NPHI), resistivity (ROEEP), pseudo-VSH (shale volume), lithology (LITHO), and fluid type (FLUIDE). Tools, designed to acquire logging data are lowered into the borehole at the end of a cable that connects them to the surface instruments controlling the operations; these instruments are housed either in a truck or in a fixed

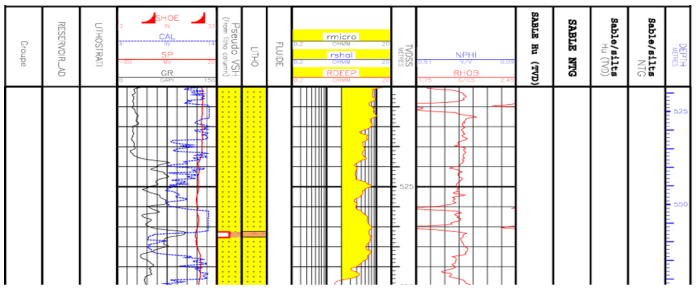

Figure 1 Geological data from the PX well

cabin for offshore drilling.

A multi-zone completion design is a method used to produce oil and gas from two or more separate layers in the same well. The main strategies are comingled flow, segregated production, and alternate zone production. This zone is designed and configured with a single-string comingled (which uses one pipe, mix fluids together, and is cheap but hard to control if pressures differ), single-string selective (which uses packers and sliding sleeves on one pipe to open or close zones one at a time), and a multiple-string (which uses two or more separate parallel pipes to produce each layer completely apart from the others). In addition, consist of zonal insolation packers set between layers to stop fluids from mixing outside the pipe, the flow control sliding sleeves or smart valves (intelligent well valves) for opening and closing holes to let oil in and the monitoring downhole sensors to track pressure and heat in each layer to check production rates.

Justification for the Completion Design

We propose using a multi-zone completion, mixed via a single production string in well PX, which has two reservoirs: one being the oil reservoir and the other the gas reservoir. The factors that will determine the design using a single production string are:

Number of reservoirs: There are two production levels in reservoir R7, which contains gas, oil, and water; it should be noted that the fluid in this reservoir is highly viscous. In addition to reservoir R7, there is also reservoir R8, which contains only gas;

Available pressure data: The tube wall thickness must be strong enough to withstand bottom pressures. Two failure modes must be considered: bursting and collapse. The tube must not be subjected to pressures exceeding its nominal pressure divided by 1.1 for the tube's collapse resistance and internal yield pressure. The collapse design factor must not be less than 1.0 based on the actual differential pressure that could be applied, for example, a full annular fluid column with an empty tube column;

Length and force variations due to temperature effects depend on the variation in the average temperature within the production column. During initial completion (static condition), the average temperature of the tubing is equal to the bottom-hole temperature plus half the surface temperature. This will serve as the reference case for determining the effect of changes in force and length due to an increase or decrease in temperature;

Tubing generally constitutes the main conduit connecting the production interval to the wellhead production facilities. Consequently, the proper selection, design, and installation of tubing are essential elements of any completion system. The tubing must be sized to allow for efficient production;

The string must be designed to prevent failure due to tensile forces, internal and external pressures, and the corrosive nature of the well environment; assembly: the components of the string

must be installed without damage to ensure pressure tightness.

Water salinity refers to the concentration of dissolved salt in the water and can lead to several consequences, such as corrosion, which is generally considered the factor with the greatest negative impact on the service life and integrity of completion equipment and components. In harsh environments, components deteriorate extremely rapidly, often with dramatic consequences and requiring costly recovery or retrieval operations; fouling is caused by the accumulation of deposits on equipment due to the presence of dissolved salts. Density can be affected by the presence of salts, which can impact the operation of measurement and control equipment.

The economic factors presented go beyond the scope of the technical preparation for well completion design. However, they undeniably influence the sector. Consequently, a basic understanding of these factors and their interaction with those mentioned above is beneficial: market forces (including seasonal fluctuations and fluctuating production); taxation (including tax obligations or tax breaks); availability of investment; and, consequently, the various configurations created using the PROPER V15.0 software. In the absence of a downhole choke, since gas pressure is higher than oil pressure, the gas will rise while preventing the oil from rising.

RESULTS AND DISCUSSION

The reservoir data are presented in Table 1.

Table 1 Data for the two reservoirs of well PX

Layers	Reservoir R7	Reservoir R8
Fluids	Oil + water + gas	Gas
Sg (psi/ft)	0.403	0.307
Roof (m)	1079	1305
Base (m)	1140	1350
Pressure (psi)	1,400	3200

Table 1 presents the second set of data on the two reservoirs (S7, S8), including fluid type, specific gravity (Sg), top depth (TOP) and base depth (Base) in metres, and pressure (in PSI). After analysing the collected data, we must consider tools to enhance understanding and approach. Nodal analysis and economic evaluation are used to carry out this work. The hydrocarbon volume in the two reservoirs, R7 and R8, is estimated based on their petro-physical properties, as illustrated in Table 2.

Based on the volumetric method, Table 2 shows that the amount of oil in the R7 oil reservoir is 4.517396985×10^{10} STB, and that of gas in the R8 gas reservoir is 29.044299270×10^{6} MMscf.

Simulation results

All results from the simulations were obtained using PROSPER V15.0 software for each reservoir. Figure 2 shows the oil reservoir's nodal analysis curve before implementing the proposed completion.

Figure 2 consist of two curves: the VFP (Vertical Flow Performance) curve of the well and the IPR (Inflow Performance Relationship) curve of the reservoir. The R7 oil reservoir has no operating point (the IPR and VFP curves do not intersect) and is therefore non-eruptive (see Figure 3 for the gas reservoir IPR curve).

Table 2 Results of the estimation of the oil and gas volumes in reservoirs R7 and R8

Parameters	Oil reservoir (R7)	Gas reservoir (R8)
Thickness (m)	61	45
Porosity	RHOB : 1.980 RHOS : 2.600 RHOF : 0.870 ; Ø : 0.358	RHOB : 2.084 RHOS : 2.600 RHOF : 0.400 ; Ø : 0.235
Water resistivity (R_w)	0.7	0.6
Formation resistivity (R_t)	12.2	5.8
Water saturation (S_w)	0.446935233	0.320176957
Oil/gas saturation (S_O/S_G)	0.553064766	0.679823043
OOIP/OGIP	4.517396985×10^{10} STB	29.044299270×10^{6} MMscf

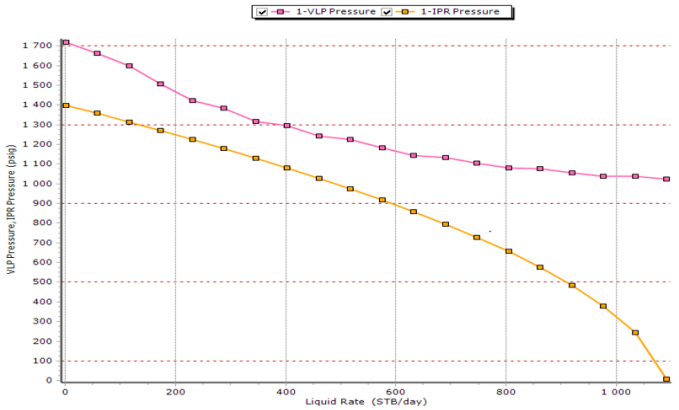

Figure 2 Nodal analysis curve of the R7 oil reservoir prior to implementation of the proposed completion

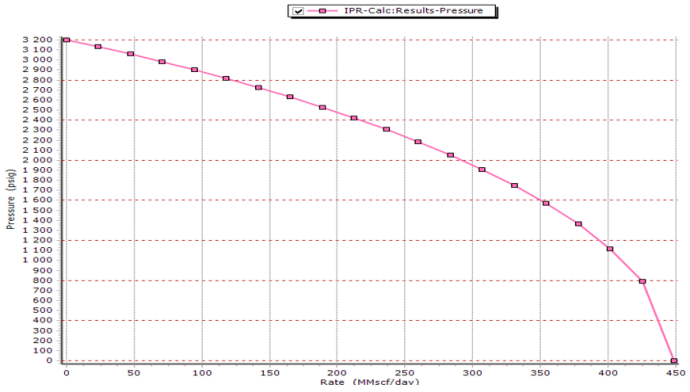

Figure 3 IPR curve for gas reservoir R8

Figure 3 shows the IPR curve for gas reservoir R8. This curve illustrates the relationship between a well's production rate and reservoir pressure. It reveals that the maximum rate that gas reservoir R8 can deliver is 448.681 MMSCF/day. Figure 4 shows the nodal analysis of gas reservoir R8.

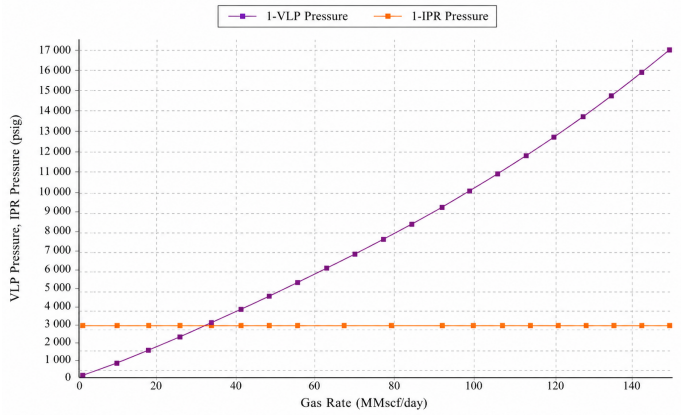

Figure 4 Nodal analysis of the R8 gas reservoir

Figure 4 consist of two curves: the VFP curve of the well and the PR curve of the reservoir. It shows that the R8 gas reservoir has an operating point where the VFP and IPR curves intersect, making it gush-prone. It can produce 35 MMscf/day. Figure 5 presents the proposed completion specification generated using Prosper V15.0, in which the goal is for the R7 oil reservoir to produce in connection with the R8 gas reservoir.

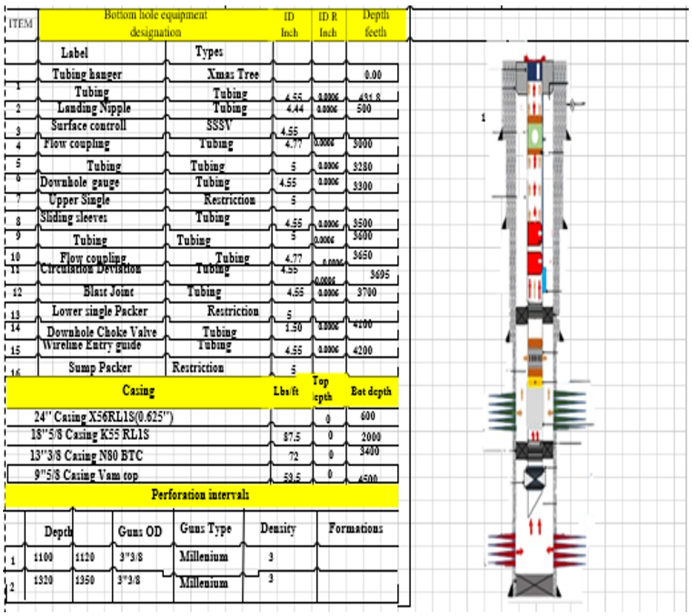

Figure 5 Proposed completion design sheet generated using Prosper V15.0

Figure 5 shows the PX well that extends into two reservoirs. The second reservoir allows the oil to rise to the surface via the downhole choke valve, which controls the flow rate of gas rising to the surface. The gas then mixes with the oil, which is highly dense. Figure 6 presents the R7 oil reservoir's nodal analysis.

Figure 6 shows the R7 oil reservoir produces oil with credit to the R8 gas reservoir. The drop in pressure as the flow rate increases indicates a possible production capacity limitation. The red curve shows how pressure changes with flow rate. A downward slope indicates a decrease in pressure as flow rate increases. The operating point is where the two curves intersect, shows that pressure and flow rate are in equilibrium for a maximum production of 2,700

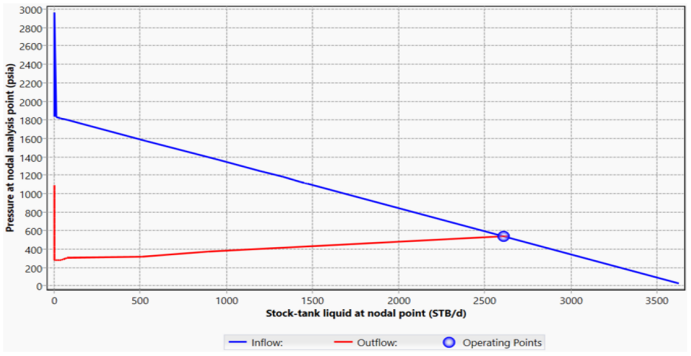

Figure 6 Nodal analysis of the R7 oil reservoir after implementation of the proposed completion

STB/d as compared to the investigation of Abeed and Khalleefah on nodal analysis calculation for the estimation of the best operating conditions using two wells for which the operating flow rate is 2500 standard barrels per day and the pressure below the well is 2200 psi in the Nafoora Field of Arabian gulf oil.

Results of the Economic Evaluation

The project's economic evaluation determines the returns for the investor. Capital and operating expenses must be considered, with revenue based on oil production, prices, taxes, the project period and costs. Table 3 shows the costs of equipment, operating expenses and capital expenditures for the proposed completion in the PX well.

Table 3 Economic model parameters

Parameters	Scenario 1	Scenario 2	Scenario 3
G & G	0.0	0.0	0.0
Facility Costs	16.0	20.0	24.0
CAPEX	1.0	3.0	4.0
OPEX per year	20.8	21.9	23.0
Drillex (for Well)	50.0	60.0	120.0
Maintenance cost every 3 years	3.0	6.0	9.0
Reserves (million barrels)	5.0	12.0	20.0
Oil Price	40.0	60.0	70.0
Production decline rate	100.0	0.0	0.0
Initial average daily	2,700.0	0.0	0.0
Discount rate	0.15	0.0	0.0

The economic evaluation is conducted for the three scenarios in Table 3. The oil prices per barrel for each scenario were selected based on market price fluctuations over a period of 10 years. Each of the three scenarios is defined as follows:

Scenario 1: The price per barrel of oil is estimated at $40, based on a pessimistic outlook regarding price fluctuations on the international market;

Scenario 2: The price per barrel of oil is the current price on the international market, i.e., $60;

Scenario 3: The price per barrel is estimated at $70, reflecting an optimistic outlook on the increase in the cost per barrel on the market.

Figure 7 shows the parameter estimates for the three scenarios presented in Table 3.

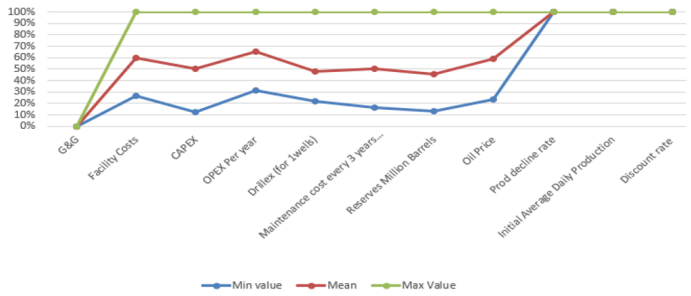

Figure 7 Estimated parameters for the three scenarios: Low (Scenario 1), Medium (Scenario 2), and High (Scenario 3), using oil production from the R7 oil reservoir via the deep-lying R8 gas reservoir

As demonstrated in Figure 7, in Scenario 1 (blue), the price per barrel of oil would be the lowest; in Scenario 2, the price per barrel of oil is the current price (brown); and in Scenario 3, the price per barrel of oil would be as high as possible (green). Tables 4-6 present the economic evaluation of the project for the three scenarios.

Table 4 Economic Evaluation of Scenario 1

Year	Prod.	Price	Revenue	CAPEX	OPEX	Cash Flow	Tax	Net CF	NPV
	(bbl/Y)	($)	(M$)	(M$)	(M$)	(M$)	15%	(M$)	(M$)
1	3.65	40	0	2.4584	21.97	-24.4284	0	-24.4284	**328.7843**
2	3.10	40	124	2.4584	21.82	99.7216	14.9582	84.76336	
3	2.70	40	108	2.4584	21.95	83.5916	12.5387	71.05286	
4	2.30	40	92	2.4584	22.28	67.2616	10.0892	57.17236	
5	1.90	40	76	2.4584	22.90	50.6416	7.59624	43.04536	
6	1.60	40	64	2.4584	22.25	39.2916	5.89374	33.39786	
7	1.40	40	56	2.4584	22.57	30.9716	4.64574	26.32586	
8	1.20	40	48	2.4584	23.59	21.9516	3.29274	18.65886	
9	1.00	40	40	2.4584	23.99	13.5516	2.03274	11.51886	
10	0.90	40	36	2.4584	24.98	8.5616	1.28424	7.27736	

Tables 4 to 6 show the NPV (net present value) for each scenario over 10 years: Scenario 1 has an NPV (1) of $328.7843, Scenario 2 has an NPV (2) of $602.4843, and Scenario 3 has an NPV (3) of $687.1949. The IRR (Internal Rate of Return) formula yields the rate of return for each scenario: Scenario 1 has an IRR (1) of 16.63%, Scenario 2 has an IRR (2) of 12.14%, and Scenario 3 has an IRR (3) of 9.62%. The cash flow is already much greater than the investment in the first year, indicating that the project remains highly profitable. The payback period is 0.8 months, or 24 days, for Scenario 1. The project is profitable.

The economic evaluation project summary for the three scenarios is presented in Figure 8 for over a period of 10 years.

Table 5 Economic Evaluation of Scenario 2

Year	Prod.	Price	Revenue	CAPEX	OPEX	Cash Flow	Tax	Net CF	NPV
	(bbl/Y)	($)	(M$)	(M$)	(M$)	(M$)	15%	(M$)	(M$)
1	3.65	60	0	2.4584	21.97	-24.4284	0	-24.4284	**602.4843**
2	3.10	60	186	2.4584	21.82	161.7220	24.2582	137.4634	
3	2.70	60	162	2.4584	21.95	137.5920	20.6387	116.9529	
4	2.30	60	138	2.4584	22.28	113.2620	16.9892	96.27236	
5	1.90	60	114	2.4584	22.90	88.6416	13.29624	75.34536	
6	1.60	60	96	2.4584	22.25	71.2916	10.69374	60.59786	
7	1.40	60	84	2.4584	22.57	58.9716	8.84574	50.12586	
8	1.20	60	72	2.4584	23.59	45.9516	6.89274	39.05886	
9	1.00	60	60	2.4584	23.99	33.5516	5.03274	28.51886	
10	0.90	60	54	2.4584	24.98	26.5616	3.98424	22.57736	

Table 6 Economic Evaluation of Scenario 3

Year	Prod.	Price	Revenue	CAPEX	OPEX	Cash Flow	Tax	Net CF	NPV
	(bbl/Y)	($/bbl)	(M$)	(M$)	(M$)	(M$)	15%	(M$)	(M$)
1	3.65	70	0	2.4584	21.97	-24.4284	0	-24.4284	**687.1949**
2	3.10	70	217	2.4584	21.82	99.2160	14.9582	87.76338	
3	2.70	70	189	2.4584	21.95	192.7220	28.9082	163.8134	
4	2.30	70	161	2.4584	22.28	136.2620	20.4392	115.8224	
5	1.90	70	133	2.4584	22.90	107.6420	16.1462	91.49536	
6	1.60	70	112	2.4584	22.25	87.2916	13.0937	74.19786	
7	1.40	70	98	2.4584	22.57	72.9716	10.9457	62.02586	
8	1.20	70	84	2.4584	23.59	57.9516	8.69274	49.25886	
9	1.00	70	70	2.4584	23.99	43.5516	6.53274	37.01886	
10	0.90	70	63	2.4584	24.98	35.5616	5.33424	30.22736	

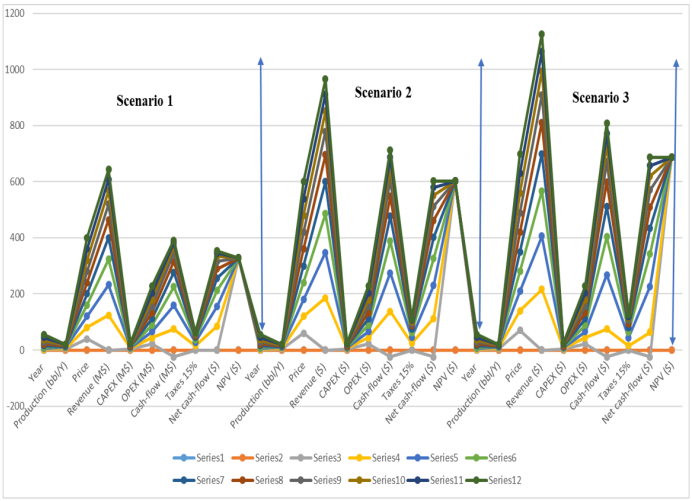

Figure 8 Economic evaluation project summary for the three scenarios

CONCLUSION

The aim of this paper was to produce oil from the PX well in the BX basin using its oil reservoir, aided by its deep-seated gas reservoir. The paper presented the data, tools, and methodology applied to address the productivity issue in the PX well, demonstrating the optimal completion design for this well. The results were then interpreted to explain the concepts discussed in the paper. The materials and methods used, including nodal analysis, economic evaluation, and the software Prosper v15.0 and Microsoft Excel, were then presented for data analysis, petro-physical analysis,

porosity, water, oil, and gas saturation, water and formation resistivity, and the estimation of in-place oil and gas volumes in the R7 oil and R8 gas reservoirs of the PX well. The R7 oil reservoir of well PX has a thickness of 61 m, a pressure of 1,400 psi, and an initial oil of $4.517396985 \times 10^{10}$ STB. The gas reservoir of well PX has a thickness of 41 m, a pressure of 3,200 psi, and an initial gas volume of $29,04429927 \times 10^{6}$ MMscf. The nodal analysis of the R7 oil reservoir of well PX prior to the implementation of the proposed completion indicated that it is non-eruptive. The nodal analysis of the R8 gas reservoir indicated that it is eruptive and can produce 35 MMscf/day.

A multi-zone completion, mixed through a single production string in the PX well, was proposed to produce oil from the R7 reservoir and gas from the R8 reservoir. After implementation, the R7 reservoir produced 2,700 STB/d as compared to the investigation of Abeed and Khalleefah on nodal analysis calculation for the estimation of the best operating conditions using two wells for which the operating flow rate is 2500 standard barrels per day and the pressure below the well is 2200 psi in the Nafoora Field of Arabian gulf oil. The economic evaluation showed that Scenario 1 had an NPV (1) of $328,7843 and an IRR (1) of 16.63%, Scenario 2 had an NPV (2) of $602.4843 and an IRR (2) of 12.14%, and Scenario 3 had an NPV (3) of $687.1949 and an IRR (3) of 9.62%. The payback period was 0.8 months (24 days) for Scenario 1. It was shown that oil production from the R7 reservoir is profitable, regardless of price.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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An Empirical Comparison of Deep Learning Models for Stock Direction Prediction: Evidence from Delta Air Lines

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ABSTRACT In this study, deep learning-based binary classification models were developed and compared in order to predict the closing direction (up/down) of Delta Air Lines (DAL) stock on the next business day. Three feature sets including technical indicators, competitor airline stocks, and market/sector representatives were derived from daily data for the period of April 30, 2015–April 17, 2026. Nine experiments were conducted with Multilayer Perceptron (MLP), Long Short-Term Memory (LSTM), and Gated Recurrent Unit (GRU) architectures. The highest accuracy and F1 score were obtained by the MLP model using only DAL technical indicators (accuracy = 52.74%; F1 = 0.489), whereas the GRU model using only DAL technical indicators produced the marginally highest ROC-AUC (0.525). However, the performance values remained only slightly above the simple comparison benchmark; competitor and market variables did not provide a consistent improvement. The findings indicate that past price/volume-based technical indicators had limited predictive value for next-day direction prediction. Within the examined stock, period, feature space, and experimental design, the results provide no evidence against the weak-form Efficient Market Hypothesis. Thus, the study points to the limits of the examined technical analysis-based approach.

KEYWORDS
Deep learning
Stock direction prediction
LSTM
Gated recurrent unit
Multilayer perceptron
Efficient market hypothesis

INTRODUCTION

Predicting the direction of stock prices in financial markets is an important but difficult problem in terms of investment decisions, risk management, and portfolio construction processes. Daily price movements are affected not only by past price and volume values, but also by news flow, sector expectations, macroeconomic conditions, and investor behaviors. Therefore, stock direction prediction should be addressed as a problem of extracting a short-term and generalizable signal from past observations. The weak-form Efficient Market Hypothesis argues that past price and volume information is reflected in current prices, and therefore it is difficult to obtain consistently superior returns through technical analysis approaches based solely on historical price information (Fama 1970; Malkiel 2003). This study examines this issue on Delta Air Lines (DAL) stock using deep learning models and interprets the results in relation to the weak-form Efficient Market Hypothesis.

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Technical analysis indicators are widely used in financial decision support systems by transforming trend, momentum, volatility, and volume information into numerical variables. Moving averages, MACD, RSI, ATR, and Bollinger Bands are among the most frequently used indicators in this context (Appel 2005; Bollinger 2002; Brock *et al.* 1992; Wilder 1978). Deep learning methods, on the other hand, stand out in financial forecasting studies due to their capacity to represent nonlinear relationships (Berat Sezer *et al.* 2019; Fischer and Krauss 2018; LeCun *et al.* 2015). In particular, gated recurrent networks such as LSTM and GRU were developed to model sequential dependencies in time series data (Bengio *et al.* 1994; Cho *et al.* 2014; Hochreiter 1997). However, when financial series have a low signal-to-noise ratio, it is not guaranteed that more complex architectures will provide higher test performance (Berat Sezer *et al.* 2019; LeCun *et al.* 2015; Srivastava *et al.* 2014).

The aim of this study is to show to what extent the closing direction of DAL stock on the next business day can be predicted using only DAL technical indicators, competitor airline stocks, and market/sector representatives. For this purpose, MLP, LSTM, and GRU models were compared on three feature sets under the same data split and the same evaluation metrics. Thus, rather than only reporting the best model, the study also makes visible the limits of technical indicator-based deep learning approaches

in short-term direction prediction. The remainder of the paper is organized as follows: Section 2 reviews the related literature, Section 3 describes the dataset, Section 4 presents the methodology, Section 5 reports the findings, and Sections 6 and 7 provide the discussion and conclusion.

LITERATURE REVIEW

The literature relevant to this study can be grouped into three strands: the debate on market efficiency and the informational content of past prices, machine learning approaches that frame stock movement as a classification problem, and the more recent wave of deep learning applications in financial forecasting. The question of whether future price movements can be inferred from past market data has been debated since the formalization of the Efficient Market Hypothesis (Fama 1970; Malkiel 2003). Timmermann and Granger (2004) argue that predictability in financial markets tends to be self-limiting: once a profitable pattern becomes widely known, its exploitation erodes the signal that produced it, so that forecasting success is expected to be local and transient rather than persistent.

The empirical evidence on technical analysis is correspondingly mixed. Brock *et al.* (1992) found that simple moving-average and trading-range rules carried predictive content for the Dow Jones Industrial Average, and Lo *et al.* (2000) showed, using nonparametric pattern recognition, that several widely used chart patterns provide incremental information about the conditional distribution of returns, although this does not necessarily translate into profitable trading. Reviewing approximately one hundred modern studies, Irwin (2007) report that positive findings on the profitability of technical trading rules are frequently weakened by data-snooping bias, ex-post rule selection, and transaction costs. The present study is situated within this debate, as its results are interpreted in relation to the weak form of the hypothesis.

A second strand of the literature frames next-period stock movement as a binary classification problem rather than a level-estimation problem. Leung *et al.* (2000) compared classification and level-estimation models on major stock indices and found that direction-based classification models generally led to better trading performance than models forecasting the level of returns, which motivates the direction-prediction design adopted in this study. Kara *et al.* (2011) predicted the daily direction of the Istanbul Stock Exchange National 100 Index using artificial neural networks and support vector machines fed with ten technical indicators and reported average accuracies of around 75% for the neural network model.

Patel *et al.* (2015) showed on Indian stocks and indices that converting continuous technical indicators into trend-deterministic (discretized) signals improved the performance of four machine learning classifiers. Ballings *et al.* (2015) benchmarked ensemble methods against single classifiers for one-year-ahead price direction over a large sample of European stocks and found that random forests ranked among the top performing algorithms. Zhong and Enke (2017) combined dimensionality reduction techniques with neural networks to forecast the daily direction of the S&P 500 ETF and obtained accuracies only modestly above benchmark levels. It should be noted that the comparatively high accuracies in this strand are typically obtained at the index level, over longer horizons, or with discretized inputs, whereas daily direction prediction for an individual stock tends to yield accuracies much closer to 50% (Fischer and Krauss 2018; Krauss *et al.* 2016).

The third strand concerns deep learning. Early surveys of soft computing methods for market forecasting (Atsalakis and Valavanis 2009) already documented the dominance of neural approaches, and more recent systematic reviews (Berat Sezer *et al.* 2019; Bustos and Pomares-Quimbaya 2020; Jiang 2021; Kumbure *et al.* 2022) show that LSTM has become the most frequently used architecture in financial time series forecasting, with technical indicators remaining among the most common input categories (Kumbure *et al.* 2022). On the empirical side, Fischer and Krauss (2018) found that LSTM networks outperformed memoryless models such as random forests and logistic regression for daily directional prediction over the S&P 500 universe, although the advantage weakened in later subperiods; notably, their reported daily directional accuracy of approximately 54% illustrates the narrow margins attainable in this problem. In an earlier study on the same universe, Krauss *et al.* (2016) found that individual deep neural networks were outperformed by gradient-boosted trees and random forests, with profitable signals largely disappearing in recent years.

Nelson *et al.* (2017) and Bao *et al.* (2017) reported favorable results for LSTM-based direction prediction and hybrid wavelet-autoencoder-LSTM frameworks, respectively, while Shen and Shafiq (2020) emphasized the role of extensive feature engineering rather than architecture alone. Chong *et al.* (2017) examined deep feature representations on intraday Korean stock returns and reported only modest gains over autoregressive baselines, concluding that deep learning offers no automatic improvement. More recently, attention-based architectures have also entered this literature: Wang *et al.* (2022) applied a deep Transformer model to the prediction of major stock market indices and reported that it can outperform recurrent baselines in back-testing experiments, while the systematic survey of Olorunnimbe and Viktor (2023) cautions that many reported successes in this field rest on backtesting protocols whose realism and reproducibility vary considerably.

Finally, a growing body of work cautions against expecting complex models to dominate in low signal-to-noise settings. Makridakis *et al.* (2018) showed in a large-scale forecasting competition setting that classical statistical methods outperformed popular machine learning methods across horizons. In the asset pricing domain, Gu *et al.* (2020) found that although machine learning improves out-of-sample return prediction mainly through regularization and the capture of nonlinear interactions, the monthly out-of-sample predictive R-squared for individual stocks remains below one percent, underscoring how weak the exploitable signal is at the level of single securities. These findings are consistent with the argument that more expressive architectures do not guarantee better generalization in financial data (Berat Sezer *et al.* 2019; LeCun *et al.* 2015; Srivastava *et al.* 2014). On the other hand, Kelly *et al.* (2024) have recently argued, both theoretically and empirically, that heavily parameterized models can improve out-of-sample return prediction despite apparent overfitting, so the relationship between model complexity and predictive success in finance remains an open question.

Taken together, the literature shows strong but heterogeneous evidence: reported accuracies vary widely with the target market, aggregation level, forecast horizon, input representation, and validation protocol, and several influential results rely on random data splits or tuning choices that are vulnerable to information leakage. Comparatively few studies offer a controlled comparison of feedforward and recurrent architectures on a single liquid stock under a strictly chronological split, leakage-free scaling, and an identical training protocol. The present study addresses this setting for Delta Air Lines, additionally testing whether competitor and market/sector context variables add predictive value, and interprets the resulting near-benchmark performance in relation to the

weak-form Efficient Market Hypothesis (Fama 1970; Timmermann and Granger 2004).

DATASET

Raw data were downloaded from Yahoo Finance in daily OHLCV format. The initial download was performed for the 2010–2026 range; however, due to the starting date of the JETS ETF data, all symbols were aligned on the common trading days of April 30, 2015–April 17, 2026. After removing missing rows resulting from technical indicators and the last-day label, the final modeling data set consisted of 2,736 observations. The target variable is a binary label indicating whether the closing price of DAL stock on day t+1 is higher than on day t; 1 represents an increase, while 0 represents a decrease or a flat closing. The data sets used and the split structure are summarized in Table 1.

Table 1 Summary of Feature Sets and Data Split

Dataset	Content	Features	Total	Train/Val./Test	Seq. Test
Dataset 1	Only DAL technical indicators	22	2,736	1,915 / 273 / 548	528
Dataset 2	DAL + UAL, AAL, LUV + competitor summaries	38	2,736	1,915 / 273 / 548	528
Dataset 3	DAL + competitors + JETS/SPY + difference variables	42	2,736	1,915 / 273 / 548	528

The class distribution is balanced: 1,349 observations were calculated as class-0 (49.31%) and 1,387 observations as class-1 (50.69%). Therefore, no additional class balancing procedure was applied. The training, validation, and test split was not performed randomly; in order to preserve the time series structure, it was divided chronologically as 70%/10%/20%. The closing prices of DAL, competitor stocks, and market/sector representatives on common trading days are given in Figure 1.

Figure 1 Closing prices aligned according to common trading days

Feature engineering is three-layered. In the first layer, daily return, gap return, intraday high-low range, moving averages, EMA12/EMA26, MACD, RSI-14, ROC-10, Bollinger bandwidth, ATR-14, and volume change ratio were calculated for DAL. In the second layer, daily return, volume change, RSI-14, and MA5/MA20 ratio were derived for UAL, AAL, and LUV stocks; in the third layer, JETS and SPY returns and the difference between DAL return and the competitor and sector averages were added. Normalization was performed using StandardScaler fitted only on the training data, and the same scaler was applied to the validation and test data (Pedregosa *et al.* 2011).

The correlation structure between selected technical and contextual variables is given in Figure 2. The matrix shows that some indicators naturally move together, whereas the added competitor and market variables may not produce a strong discriminative signal on their own for target direction prediction.

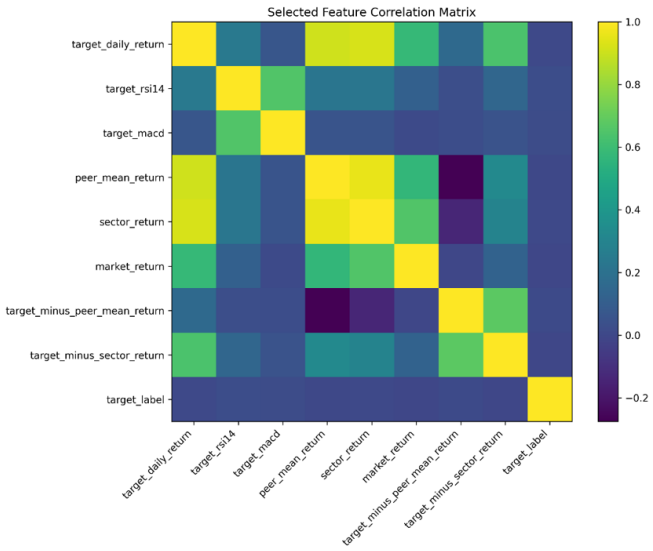

Figure 2 Correlation matrix for selected features

METHOD

Three architectures were compared in the study. MLP is a two-hidden-layer model that classifies the normalized tabular features belonging to the same day without constructing a sequence structure. LSTM is a gated recurrent network that takes a 20-day feature window as input and models temporal dependencies through its memory cell and input/forget/output gates (Bengio *et al.* 1994; Hochreiter 1997). GRU, on the other hand, has a simpler structure than LSTM with its update and reset gates (Cho *et al.* 2014). Thus, a memoryless tabular structure, a more complex memory mechanism, and a simpler gated structure were compared on the same problem.

All experiments were implemented with PyTorch, and the Adam optimizer was used (Kingma and Ba 2014; Paszke *et al.* 2019). The loss function was set as BCEWithLogitsLoss, the decision threshold as 0.50, the learning rate as 0.001, the batch size as 32, the maximum number of epochs as 100, the early stopping patience value as 15, and the random seed as 42. In the MLP, two fully connected layers with 128 and 64 neurons, ReLU activation, and dropout were used; in the LSTM/GRU models, a single recurrent layer with 64 hidden units, dropout, and a fully connected layer with 32 neurons were used. Performance was measured with accuracy, precision, recall, F1, and ROC-AUC metrics. The weights at the epoch with the lowest validation loss were saved, and the test results were reported only with this model. The parameters used and their values are given in Table 2.

FINDINGS

The test results of the nine experiments consisting of three models and three feature sets are given in Table 3. The highest accuracy

Table 2 Training Protocol and Hyperparameters

Parameter	Value
Maximum epochs	100
Lookback window	20 days
Learning rate	0.001
Loss function	BCEWithLogitsLoss
Data split	70% / 10% / 20% (chronological)
Early stopping	15 epochs
Batch size	32
Optimizer	Adam
Feature scaling	StandardScaler
Random seed	42

and F1 score were obtained in Exp-01, in which the MLP was trained only with DAL technical indicators (accuracy = 52.74%; F1 = 0.489). In contrast, Exp-07, which used a GRU with the same DAL-only feature set, produced the marginally highest ROC-AUC (0.525), compared with 0.524 for Exp-01. Nevertheless, all of these values indicate limited discriminative performance in a problem with an approximately balanced class distribution.

When the results in Table 3 are evaluated together in terms of model family and feature set, it is seen that the addition of competitor and market variables did not provide a consistent improvement. The F1 value achieved by the MLP using only DAL data decreased in the broader feature sets. The detailed outputs of Exp-01, which is the best model, also confirm the limited discriminative power. The confusion matrix shows 165 true negatives and 113 false positives for class-0; and 124 true positives and 146 false negatives for class-1. In other words, the model missed a significant portion of the upward days. Based on the same confusion matrix, the class-0 F1 score was 0.560 and the class-1 F1 score was 0.489, resulting in a macro-F1 score of 0.525. The balanced accuracy, calculated as the mean of the class-1 recall (0.459) and the class-0 recall, or specificity (0.594), was 0.526. These class-balanced metrics also indicate that the model had limited discriminative performance across the two classes. This finding is presented in Figure 3 together with the ROC curve. In Figure 4, the loss and accuracy curves of the MLP model are given. While the training loss decreases, the fluctuating course of the validation loss shows that the model could not provide a stable improvement on the validation data. Although the training accuracy increases, the validation accuracy remaining limited supports that the model's generalization power is weak.

Table 3 Test Set Performance Results

Exp.	Model	Feature Set	Acc.	Prec.	Recall	F1	AUC
Exp-01	MLP	Only DAL	52.74	52.32	45.93	0.489	0.524
Exp-02	MLP	DAL + Competitors	50.00	48.94	34.07	0.402	0.500
Exp-03	MLP	DAL + Competitors + Market	47.81	46.85	44.07	0.454	0.467
Exp-04	LSTM	Only DAL	49.81	46.34	22.27	0.301	0.520
Exp-05	LSTM	DAL + Competitors	47.73	43.42	25.78	0.324	0.508
Exp-06	LSTM	DAL + Competitors + Market	51.14	49.40	32.03	0.389	0.516
Exp-07	GRU	Only DAL	48.30	44.14	25.00	0.319	0.525
Exp-08	GRU	DAL + Competitors	51.33	49.68	30.08	0.375	0.511
Exp-09	GRU	DAL + Competitors + Market	49.62	47.47	36.72	0.414	0.488

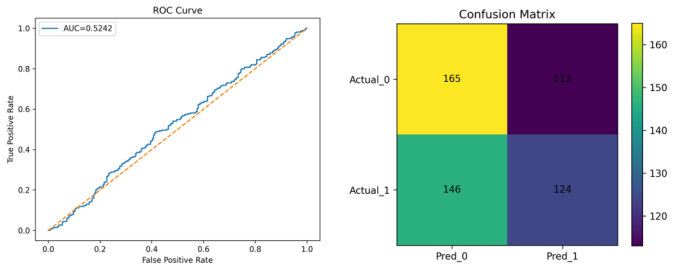

Figure 3 ROC curve and confusion matrix for Exp-01

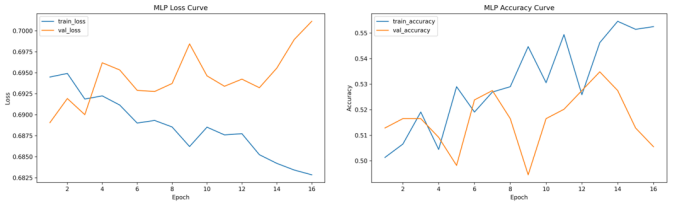

Figure 4 Training loss and accuracy curves for Exp-01

DISCUSSION

The findings provide no evidence against the weak-form Efficient Market Hypothesis within the examined stock, period, feature space, and experimental design. The technical indicators derived from past price and volume information did not strongly distinguish the next-day direction of DAL stock (Fama 1970; Malkiel 2003). This result does not mean that technical indicators are entirely dysfunctional; however, it shows that, within the examined period, target definition, and modeling framework, they did not produce a sufficient prediction signal on their own. In addition, the inability of LSTM and GRU to provide a clear superiority over MLP indicates that complex sequential architectures may not automatically be more successful in financial direction prediction (Berat Sezer *et al.* 2019; LeCun *et al.* 2015; Srivastava *et al.* 2014). When compared with literature, the results indicate differences in conditions rather than contradiction. Fischer and Krauss (Fischer and Krauss 2018) reported that LSTM could provide superiority in some periods within a broad S&P 500 universe; Nelson et al. (Nelson *et al.* 2017) reported the use of LSTM for stock movement direction; and Bao et al. (Bao *et al.* 2017) reported a hybrid framework that supports LSTM with preprocessing and representation learning components. In contrast, studies using news, events, or multi-source data show that additional information domains beyond price history may strengthen prediction (Ding *et al.* 2015; Zhang *et al.* 2018). This comparison is summarized in Table 4.

Table 4 shows that the result of this study should be interpreted not as "deep learning does not work in financial forecasting," but as "short-term direction prediction for DAL remained limited when only technical indicators and nearby market context were used." The addition of competitor stock and ETF variables did not produce information gain; on the contrary, in some experiments, it may have increased noise and model complexity. Therefore, in future studies, richer sources such as rolling-window validation, feature selection, backtests including transaction costs, and news/sentiment data should be tested (Berat Sezer *et al.* 2019; Ding *et al.* 2015; Zhang *et al.* 2018).

Table 4 Comparison of the findings with the literature

Study	Data / Approach	Main Emphasis in the Literature	Relationship with the Present Study
Brock et al. (Brock *et al.* 1992)	Technical trading rules on the DJIA	Shows that some technical rules may carry signals against the random walk.	In the DAL case, technical features did not produce a strong signal in the short term.
Fischer and Krauss (Fischer and Krauss 2018)	S&P 500 constituents, LSTM	LSTM may outperform memoryless models in some periods.	No superiority of LSTM/GRU was observed for a single stock in the 2015–2026 period.
Nelson et al. (Nelson *et al.* 2017)	LSTM for stock direction	Direction prediction based on price history is possible, but the problem is difficult.	In this study, LSTM recall remained low.
Bao et al. (Bao *et al.* 2017)	WT + SAE + LSTM hybrid framework	Hybrid preprocessing/representation learning may improve performance.	Standard technical indicators and a simple LSTM were not sufficient.
Ding et al. (Ding *et al.* 2015); Zhang et al. (Zhang *et al.* 2018)	News/event/social media and multi-source data	Additional information sources may contribute to the prediction of price movement.	News, sentiment, and macro data should be added in future studies.

CONCLUSION

In this study, MLP, LSTM, and GRU models were systematically compared on three different feature sets in order to predict the closing direction of DAL stock on the next business day. The highest accuracy and F1 score were obtained by the MLP model trained only with DAL technical indicators (accuracy = 52.74%; F1 = 0.489), whereas the GRU model using the same DAL-only feature set produced the marginally highest ROC-AUC (0.525). However, these results indicated limited predictive power across all examined models. The addition of competitor stock and market/sector ETF variables did not provide a consistent improvement, and the LSTM and GRU models did not show a clear superiority over MLP. As a result, past price/volume-based technical indicators did not provide strong predictive performance on their own in the examined short-term direction prediction setting. Within the examined stock, period, feature space, and experimental design, the findings provide no evidence against the weak-form Efficient Market Hypothesis.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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