Widyakala Journal
p-ISSN 2337-7313
e-ISSN 2597-8624

Volume 12, Issue 01, March 2025
DOI: https://doi.org/10.36262/widyakala.v12i1.1149
https://ojs.upj.ac.id/index.php/journal_widya/

Digital Adaptation Strategies for Enhancing MSME Resilience Against Extreme Weather in Urban Contexts

IGN Oka Ariwangsa[1], Komang Widhya Sedana Putra P[2*]

[1]Program Studi Ekonomi dan Bisnis, Universitas Pendidikan Nasional
Denpasar, Bali 80224, Indonesia
okaariwangsa@undiknas.ac.id
[2]Program Studi Ekonomi dan Bisnis, Universitas Pendidikan Nasional
Denpasar, Bali 80224, Indonesia
widhyasedana@undiknas.ac.id*
*Email korespondensi penulis

Received 07 January 2025, Revised 21 January 2025, Accepted 03 February 2025

Abstract — *More frequent extreme weather conditions disrupt urban ecosystems and the sustainability of MSMEs, crucial contributors to the local economy. This paper seeks to explore extreme weather conditions' impacts on MSMEs in Denpasar, Indonesia, and the mitigation role of digital technologies using IoT and GIS for environmental risk mitigation. This study employs a quantitative approach by using PLS-SEM in order to analyze the interactions between extreme weather, digital adaptation strategies, and the sustainability of MSMEs. It was found that extreme weather negatively impacts the operation and financial stability of MSMEs, while digital adaptation strategies have significantly improved their resilience and sustainability. The originality of this study lies in integrating resilience theory and technological determinism to address the challenges of urban MSMEs. Recommendations on how to strategically facilitate digital transformation to enhance operational efficiency for sustainable urban development are provided.*
Keywords: *MSME Resilience, Extreme Weather, Digital Adaptation, Sustainable Development*

Abstrak — Kondisi cuaca ekstrem yang semakin sering terjadi mengganggu ekosistem perkotaan dan keberlanjutan UMKM, yang merupakan kontributor penting bagi perekonomian lokal. Penelitian ini bertujuan untuk mengeksplorasi dampak kondisi cuaca ekstrem terhadap UMKM di Denpasar, Indonesia, serta peran mitigasi teknologi digital menggunakan IoT dan GIS dalam pengelolaan risiko lingkungan. Studi ini menggunakan pendekatan kuantitatif dengan PLS-SEM untuk menganalisis interaksi antara cuaca ekstrem, strategi adaptasi digital, dan keberlanjutan UMKM. Hasil penelitian menunjukkan bahwa cuaca ekstrem berdampak negatif terhadap operasional dan stabilitas keuangan UMKM, sementara strategi adaptasi digital secara signifikan meningkatkan ketahanan dan keberlanjutan mereka. Keaslian penelitian ini terletak pada integrasi teori resiliensi dan determinisme teknologi untuk mengatasi tantangan yang dihadapi UMKM perkotaan. Rekomendasi diberikan mengenai cara memfasilitasi transformasi digital secara strategis untuk meningkatkan efisiensi operasional dalam mendukung pembangunan perkotaan yang berkelanjutan.
Kata Kunci: Ketahanan UMKM, Cuaca Ekstrem, Adaptasi Digital, Pembangunan Berkelanjutan

INTRODUCTION

Extreme weather events, such as heatwaves and heavy rainfall, strain urban ecosystems by overwhelming stormwater systems and increasing the risk of flooding, which jeopardizes the effectiveness of green infrastructure in managing water (Pandey & Ghosh, 2023). Climate change also alters habitats and species distributions, with rising temperatures threatening sensitive tree species like maples, vulnerable to heat and drought conditions (McPhearson et al., 2018). Many cities, particularly those in coastal areas or near rivers, are at heightened risk of flooding due to rising sea levels and increased precipitation (IPCC, 2022). These urban hubs of economic activity, innovation, and social interaction face direct impacts from extreme weather changes, including floods, heatwaves, strong winds, and shifting rainfall patterns. These risks disrupt not only physical infrastructure and public services but also different economic sectors that include micro, small, and medium enterprises. The MSMEs constitute the backbone of the local economy and make vital contributions to job creation and social stability. However, their resilience in the case of extreme weather changes is often limited because of resource, knowledge, and adaptive technological constraints. This limited access further exacerbates their vulnerability, as many MSMEs cannot leverage

innovative solutions that could enhance their resilience (Myanmar et al., 2024).

Emphasizing digitalization in operational processes can enhance the resilience of MSMEs. The continuity of MSMEs during natural disasters, however, needs to be grounded on more adaptive and resilient strategy implementations. Those businesses which use technology in marketing, transactions, and communication will more easily be able to resist a crisis such as the COVID-19 pandemic (Kurniawan et al., 2023). Maintaining customer satisfaction is one of the best practices that service providers can implement (Sitorus & Montana, 2023). MSMEs can become agents of change within dynamic urban contexts by adopting sustainable business practices that involve efficient use of resources, clean technologies, and data-driven risk management strategies. None of these will be possible without leveraging digital technologies that drive informed decision-making. As society evolves and technology advances, people find themselves with new needs beyond their basic necessities (Tresna & Sijabat, 2023). Technologies such as IoT, GIS, and data-driven applications can help MSMEs tackle climate change challenges by monitoring environmental risks, improving operational efficiency, and creating new business opportunities. IoT enables the collection of real-time data on energy consumption and environmental conditions, thus enabling businesses to optimize energy use, reduce costs, and lower carbon footprints, which in turn contribute to sustainability and climate goals. This is according to (Alshahrani et al., 2024).

Despite these possibilities, there are considerable research gaps in the existing literature. First, most of the past studies have focused more on macroeconomic approaches and global policies without delving into the specific challenges that MSMEs face in urban areas. This relative lack of attention is partly due to the limited availability of empirical data on urban MSMEs, since most studies aggregate data without differentiating between urban and rural enterprises. Urban MSMEs have specific binding constraints, such as high operational costs, complex regulatory environments, and vulnerabilities to extreme weather, which are not well represented in broader studies.

Secondly, although the potential role of digital technologies in climate adaptation has been identified, previous research rarely explores how these technologies are practically integrated into MSME sustainability strategies. This is partly because of some challenges, for instance, high adoption cost in technologies like IoT and GIS. The technical know-how within the MSMEs is limited and there are no local case studies, which demonstrate practical implementations. Lack of detailed research on these aspects barred comprehensive insight into how digital solutions support resilience and sustainability in urban MSME contexts.

Third, most past studies are anchored in the context of rural economy or agriculture that comes at a cost to a comprehensive study about the urban arena and all its facets and social arrangements. As much as their rural contemporaries, typically, more operational MSMEs have been often located in overpopulated, competition-driven, highly resource-scarce urban settings and thus depend, for example, on such complicated supply lines that may likely be vulnerable in the event of an extreme natural event.

Therefore, the paper addresses such lacunae through the integration of approaches to explain the relationships among extreme weather changes, the sustainability of MSMEs, and technology-driven adaptation measures in an urban environment. It assembles empirical data with collection focus on IoT, GIS, and data-driven application usage and represents the multi-level analysis of problems and opportunities of urban MSMEs. It goes further to make strategic recommendations that would support the digital transformation of MSMEs, address policy gaps, and best practices toward the attainment of sustainable urban development.

The novelty of this research is the integration of MSMEs, digital technologies, and urban contexts with the challenges caused by extreme changes in weather. Cities are becoming smart driven by digital transformation and urbanization. They offer completely new ways in which urban space is improved and lived. Widhya et al. (2024). This study theoretically contributes to the literature on sustainability and technological adaptation, while it also provides practical solutions for policymakers and MSME practitioners in building more resilient, inclusive, and sustainable cities. Hence, this study will provide a sound foundation for the development of effective adaptation strategies that match the future needs of urban societies.

In this study, two grand theories are very relevant as the foundation to understand the dynamics of facing extreme weather change and MSME sustainability in urban areas. First, Resilience Theory emphasizes the capacity of individuals, communities, or systems to absorb, adapt, and endure disruptions or changes, including climate change. Resilience is commonly defined as the ability of a dynamic system to successfully adapt to disturbances that threaten its viability, which allows for a broad application across various levels of analysis, from molecular to societal contexts (Southwick et al., 2014). The Intergovernmental Panel on Climate Change (IPCC) defines resilience as the capacity of social and ecological systems to absorb disturbances while retaining their essential functions and structures, which includes self-organization and adaptation capabilities (Ramanathan et al., 2022).

This theory has been elaborated to explain how MSMEs in urban areas can adapt to extreme weather impacts, with technology integration playing a key role in enhancing their resilience. Digital tools for

marketing, supply chain management, and customer engagement enable the continuity of business even during disruptions for better adaptation to environmental challenges (Dima et al., 2023). In the application of this theory in the research, resilience principles such as resource diversification, strengthening technological capacity, and strategies of innovation explain how MSMEs can maintain operational sustainability amidst environmental challenges. Resilience Theory supports the development of digital technologies as adaptation tools that enhance business sustainability and foster resilient urban development. Digital transformation greatly enhances organizational resilience, especially in crises like the COVID-19 pandemic. Companies that adapted their digital capabilities—such as virtual access, collaboration, and data-driven decision-making—demonstrated improved adaptability and crisis management, emphasizing the critical role of digital tools in enhancing resilience and ensuring continuity in the face of disruptions (Browder et al., 2024).

Second, Technological Determinism Theory posits that social and economic changes are largely driven by technological advancements. Coined by sociologist Thorstein Veblen in the early 20th century, the concept was expanded by theorists like Clarence Ayres and William Ogburn. They argued that technological progress shapes history and social change, with society often adapting to, rather than influencing, technological developments (Hauer, 2017). This theory, in relation to this study, has been used to explain how the application of IoT and GIS technologies could guide the application of digital technology in transforming MSMEs to be sustainable amid the era of climate change. Specifically, the study shall look at how pro-active adoption of digital technologies by MSMEs would shift traditional business models toward ones that are fit for efficiency and resilient to environmental risks. This theory also explains how technological innovations drive the integration of business sustainability with smarter, environmentally conscious urban development. The development of smart cities uses advanced technologies in support of sustainable urban environments by reducing environmental impact through improved urban services using smart grids, intelligent transport systems, and eHealth technologies, which is in line with the greater goal of creating resilient and efficient cities (Mora et al., 2021).

The two theories are somewhat interlinked, in that Resilience Theory provides a conceptual framework for the needs of adaptation and mechanisms of survival in MSMEs, while the Technological Determinism Theory articulates how technology is one of the main enablers for such goals. This provides a strong base for investigating the inter-linkages among extreme weather changes, MSME sustainability, and technology-driven transformation in urban contexts using the dual theories.

Extreme Weather Impacts on Sustainable MSMEs

Severe weather events, floods, and heatwaves may alter rainfall and disrupt the conduct of business, raw material supplies, and its distribution, making MSMEs less efficient and competitive. As a result, this type of enterprise generally lacks substantial wherewithal to meet such catastrophes; thus, their productivity suffers, and hence costs inflate and supplies become disrupted enough to question long-term viability. These are particularly vulnerable for construction MSMEs, which constitute more than 99% of the total businesses in the sector. Studies have shown that they are badly affected by disruptions due to severe weather events such as heavy snowfall and flooding (Wedawatta et al., 2011). It was noted in one study that extreme weather could result in thousands of business failures, with construction firms being particularly hard hit because their operations were usually at the mercy of good weather (Ebi et al., 2020).

Extreme Weather Impacts on Digital Adaptation Strategies for Environmental Risk Management

Severe changes in weather conditions further compel MSMEs to adopt IoT, GIS, and data-driven applications to improve climate resilience. This technology enables monitoring environmental risks in real time, building better early warning systems, and faster decision-making. IoT devices, such as sensors detecting air quality or temperature change, can inform the relevant authorities of the impending danger to improve response. Lawler et al., 2020 add that extreme weather interferes with the supply chain by damaging infrastructure and making operations costlier, which urges organizations to develop risk assessment models and employ big data analytics in finding the vulnerable points of disruptions (Yun & Ülkü, 2023).

Digital Adaptation Strategies for Environmental Risk Management Impact Sustainable MSMEs

Effective digital adaptation strategies enhance MSME resilience and sustainability in facing extreme weather changes. Digital technologies help monitor and manage environmental risks, optimize resources, improve efficiency, and reduce losses from disruptions. For example, data-driven applications assist in better planning, minimizing waste, and optimizing supply flows, contributing to long-term sustainability. Digital technologies (DTs) are crucial for MSMEs to navigate environmental challenges effectively (World Economic Forum, 2024). Drones and Earth Observation technologies provide the critical insights of environmental changes and disaster impacts that support better risk assessment and response strategies (Asian Development Bank (ADB), 2021).

Digital Adaptation Strategies for Environmental Risk Management Mediate the Relationship Between Extreme Weather and Sustainable MSMEs

This hypothesis postulates that digital adaptation strategies mediate the relationship between extreme weather changes and MSME sustainability. While extreme weather conditions can have quite an impact on MSMEs, digital technologies can reduce risks and enhance the efficiency of their operations. Therefore, MSMEs are able to minimize losses amidst extreme weather conditions. In this perspective, digital adaptation becomes a critical factor in helping MSMEs transition into sustainability under challenging environmental change. Furthermore, the adoption of digital strategies corresponds to wider sustainability goals. By using technology to manage environmental risks, MSMEs not only safeguard their operations but also contribute to sustainable development goals (The Central People's Government of the People's Republic of China, 2022). This integration is vital as businesses face increasing pressure to demonstrate environmental responsibility amid rising climate challenges (Rusmayadi et al., 2023).

This hypothesis suggests that digital adaptation strategies mediate the relationship between extreme weather changes and MSME sustainability. While extreme weather can significantly impact MSMEs, digital technology can mitigate these effects by reducing risks and improving operational efficiency. This allows MSMEs to minimize losses and maintain operations despite facing extreme weather events. In this context, digital adaptation becomes a key factor in helping MSMEs transition to sustainability amidst challenging environmental changes. Moreover, the adoption of digital strategies aligns with broader sustainability goals. By using technology to manage environmental risks, MSMEs not only safeguard their operations but also contribute to sustainable development goals (The Central People's Government of the People's Republic of China, 2022). This integration is vital as businesses face increasing pressure to demonstrate environmental responsibility amid rising climate challenges (Rusmayadi et al., 2023).

METHODS

Research Location

This research was conducted in Denpasar City. The population in this case are all MSMEs operating within the tourism sector, registered in Denpasar Open Data, amounting to 28,224 units. The purposive sampling method is designed based on the following criteria of MSMEs: those suffering from extreme changes in weather ; those MSMEs which have devised their strategies to adapt to environmental alterations; and utilization of digital technologies in order to manage environmental risk. The total number used in this analysis is 200 MSMEs to meet the analysis requirements using PLS-SEM.

This research was conducted to collect data, developing quantitative methods by handing out questionnaires to the MSME owners or their managerial staff as respondents. It was designed to measure three key variables: Extreme Weather Changes, which are the physical and psychological impacts on MSME operations, such as disrupted supply chains, increased production costs, and infrastructure damage; Sustainable MSMEs, which includes the economic, environmental, and social dimensions of sustainability in relation to MSMEs due to extreme weather changes; Digital Adaptation Strategies for Environmental Risk Management, which looks upon the use of digital technologies-IoT, GIS, or data-driven applications-in predicting the impacts of extreme weathers on lowering carbon emissions and enhancing the sustainability of businesses.

Statements in the questionnaire were closed-ended in nature to draw from respondents' perceptions and attitudes regarding how extreme weather changes affect MSME sustainability, how MSMEs develop digital adaptation strategies for environmental risk management, and how the use of digital technology strengthens business sustainability in the face of extreme weather challenges. According to Roselidyawaty & Rokeman, 2024, Likert-type questions can be framed in various contexts of economics. This design enables effective data collection to measure the relationships among the variables under study.

Data Analysis

Data analysis was done using PLS-SEM version 4.0, an advanced statistical method useful in the analysis of complex relationships among variables. PLS-SEM is ideal for exploratory research, and it can analyze complex models with smaller samples and non-normal data effectively (Goktas & Dirsehan, 2024). The measurement model includes the testing steps for the validity and reliability of the constructs, testing of the structural model to assess the hypotheses, and mediation and moderation analysis. This study used mediation analysis to indicate how Digital Adaptation Strategies for Environmental Risk Management mediate the relationship between Extreme Weather Changes and Sustainable MSMEs. The process incorporated a bootstrapping technique with 5,000 resamples to ensure that the obtained results are reliable and significant.

From the results, conclusions will be drawn to give practical implications for MSMEs in promoting resilience, adapting to climate challenges, and implementing sustainability for their competitive advantage.

Complete Combined Model:

$Y_1 = \beta_0 + \beta_1 X_1 + \varepsilon$ *(1)*

$Z_1 = \beta_0 + \beta_2 X_1 + \varepsilon$ *(2)*

$Y_1 = \beta_0 + \beta_3 Z_1 + \varepsilon$ *(3)*

$Y_1 = \beta_0 + \beta_1 X_1 + \beta_4 Z_1 + \varepsilon$ *(4)*

Description

Y_1: Sustainability of MSMEs, which is the dependent variable measured in hypotheses H1 and H3.

X_1: Extreme weather changes; this is the independent variable which affects MSME sustainability and digital adaptation strategies.

Z_1: Digital adaptation strategies for environmental risk management; this is the independent variable in hypotheses H2 and H3.

β_0 = Constant or intercept in the regression model, which is the baseline value of the dependent variable before any influence from independent variables.

$\beta_1, \beta_2, \beta_3, \beta_4$ = Regression coefficients representing the degree to which each independent variable influences the dependent variable. It shows the relationship and their respective influences of the variables.

ε = Error term or disturbance, representing factors other than those explained by the model or variables measured in the study..

RESULTS AND DISCUSSION

Descriptive Analysis

Tabel 1. Descriptive Profile of the Respondents

Category	Sub-category	Frequency (n)	Percentage (%)
Gender	Male	120	60
	Female	80	40
Age	18–25 years	40	20
	26–35 years	80	40
	36–45 years	50	25
	>45 years	30	15
Educational Level	High School	50	25
	Diploma/Associate Degree	60	30
	Bachelor's Degree	70	35
	Master's Degree	20	10
Business Type	Accommodation	50	25
	Food & Beverage	60	30
	Retail	40	20
	Other Tourism Services	50	25
Years in Business	< 1 year	30	15
	1–5 years	90	45
	6–10 years	50	25
	>10 years	30	15

The descriptive profile of the respondents, as shown in Table 1, indicates that a greater number are males, 60%, while females account for 40%. Ownership or management of MSMEs in the study area is therefore male-dominated and reflects the possible gender dynamics in business leadership. Most respondents fell within the productive age bracket of 26–35 years, accounting for 40%, followed by those aged 36–45 years at 25%. This demonstrates the active participation of relatively young entrepreneurs who might be more adaptable to innovations and the adoption of technology.

In regard to education, 35% have a bachelor's degree, 30% completed their diploma or associate degree, while 25% completed high school. Only 10% had a master's degree. This shows that the majority of MSME owners or managers had an average to a high level of formal education that could affect their disposition toward adopting advanced technologies like IoT and AI.

By type of business, the largest categories were food and beverage at 30%, accommodation at 25%, other tourism services at 25%, and retail at 20%. These sectors are the most critical parts of the local economy and are very vulnerable to operational issues such as transportation inefficiencies, supply chain disruptions, and environmental concerns.

Business experience varied, with 45% of the respondents running for 1–5 years and 25% managing their businesses for 6–10 years. This shows that most

respondents have a moderate level of experience in running MSMEs, which may give them some familiarity with business challenges but also highlights potential gaps in resilience and sustainability strategies.

The sample of relatively young entrepreneurs, with different levels of education and at a diversified industrial base, presents a series of opportunities and challenges linked to the adoption of digital technologies. Younger entrepreneurs might be more open to innovation; however, their limited experience in firm management and particular vulnerabilities of sectors demand focused policies that will enhance strategic integration of technology and operational sustainability. This analysis gives deeper insights into the peculiar challenges faced by MSMEs, outlining the need for tailored interventions which must address their peculiar contexts.

Reliability and Validity Test

Table 2. Cosntruct Reliability and Validity

	Core Aspect Measured	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Digital Adaptation Strategies for Environmental Risk Management	Economic, social, and environmental dimensions: Examining how MSMEs maintain operational continuity and resilience in response to extreme weather	0.773	0.964	0.85	0.595
Extreme Weather	Impact on MSME operations: Investigating how extreme weather events disrupt operations, increase costs, and threaten business sustainability	0.753	0.976	0.818	0.572
Sustainable MSMEs	Technology adoption for risk management: Analyzing how digital strategies (e.g., IoT, GIS) are used to reduce risks and enhance sustainability	0.799	0.955	0.895	0.703

From Table 2, all three constructs are internally reliable and consistent, as evidenced by the reliability and validity data above. The Cronbach's alpha values for Digital Adaptation Strategies for Environmental Risk Management, Extreme Weather, and Sustainable MSMEs are 0.773, 0.753, and 0.799, respectively, which is well above the threshold of 0.7, regarded as acceptable for any construct to be considered reliable. Also, the composite reliability values rho_a and rho_c for all the constructs are well above the recommended threshold of 0.7. Precisely, Digital Adaptation Strategies has a composite reliability of 0.964 (rho_a) and 0.85 (rho_c), Extreme Weather shows values of 0.976 (rho_a) and 0.818 (rho_c), and for Sustainable MSMEs, the values are 0.955 (rho_a) and 0.895 (rho_c). All these values confirm that the constructs are very robust in terms of their reliability. Besides, the values of AVE for all three variables of Digital Adaptation Strategies are 0.595, Extreme Weather is 0.572, and that of Sustainable MSMEs is 0.703; hence, all values are above the threshold limit of 0.5, indicating satisfactory convergent validity. Results thus show that the constructs are reliable and valid, as dimensions have been conceptualized without substantial measurement error.

Hypothesis Test

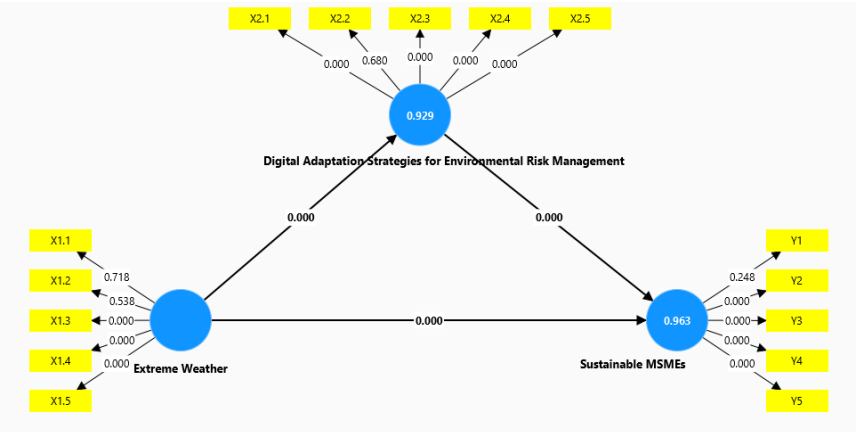

Fig 1. Structural Equation Model Testing

Table 3. Regression Weight Structural Equational Model

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Digital Adaptation Strategies for Environmental Risk Management → Sustainable MSMEs	0.552	0.566	0.096	5.761	0.000
Extreme Weather → Digital Adaptation Strategies for Environmental Risk Management	0.964	0.964	0.008	7.659	0.000
Extreme Weather → Sustainable MSMEs	0.438	0.422	0.098	4.488	0.000

From table 3, it has been observed from the analysis that there are considerable associations among the variables analyzed. For example, the path that leads from Digital Adaptation Strategies for Environmental Risk Management to Sustainable MSMEs has a coefficient of 0.552, with a positive moderate influence. This is a statistically significant relationship, as seen from the t-statistic of 5.761 being greater than the threshold of 1.96 and a p-value of 0.000, indicating that the digital adaptation strategy significantly improves the sustainability of MSMEs. Secondly, the influence of the relationship between Extreme Weather and Digital Adaptation Strategies for Environmental Risk Management has a very strong impact, with a path coefficient of 0.964. The statistical support for this observation is the t-statistic at 7.659 and the p-value of 0.000, which demonstrate that extreme events drive the adoption of digital strategies that help manage environmental risk. The path from Extreme Weather to Sustainable MSMEs has a path coefficient of 0.438, a t-statistic of 4.488, and a p-value of 0.000, which indicates that extreme weather influences the sustainability of MSMEs through various operational disruptions. Generally, all the relationships are significant, showing that digital adaptation strategies are important in mitigating the impact of extreme weather on the sustainability of MSMEs.

Table 4. Total Indirect Effect

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Extreme Weather → Digital Adaptation Strategies for Environmental Risk Management → Sustainable MSMEs	0.532	0.546	0.092	5.774	0.000

This analysis also depicts that Extreme Weather exerts an indirect impact through Digital Adaptation Strategies on environmental risk management to affect the sustainable MSMEs. The path coefficient is 0.532, showing that the relation holds good at a moderate positive magnitude. Moreover, the t-statistic value of 5.774 (exceeding the minimum threshold of 1.96) with a p-value of 0.000 will conclude the statistical significance of this particular indirect effect. This would, therefore, imply that extreme weather influences MSME sustainability directly and indirectly by influencing the adoption of digital adaptation strategies that enhance their sustainability. Again, it shows how important digital solutions are in the mitigation of environmental risks.

Discussion

The descriptive profile of respondents reveals key characteristics influencing the adoption of digital technologies for sustainability by MSME owners and managers. A majority of the respondents are male at 60%, indicating a male-dominated structure in MSMEs. Most of the respondents fall between 26–35 years of age, 40%, showing a younger and more adaptive age bracket, though they may lack experience in managing complex business challenges. Education-wise, 35% have a bachelor's degree, suggesting a moderate to high level of formal education that could facilitate technology adoption.

The sample mainly comprises food and beverage businesses at 30%, accommodation at 25%, other tourism services at 25%, and retail at 20%, all of which are operationally vulnerable. Forty-five percent of the respondents have 1–5 years of business experience, indicating a moderate level of familiarity with operations but limited experience in long-term strategic planning.

These factors highlight the opportunities and challenges that MSMEs face in adopting digital technologies. Whereas young, well-educated entrepreneurs are open to innovation, they need experience and support in integrating technologies such as IoT and GIS. Policies are needed in the direction of training, financial incentives, and access to affordable digital tools.

In this study, four hypotheses were put to test and found to be statistically significant; thus, they provided useful insights into the relationships among extreme weather, digital adaptation strategies, and the sustainability of MSMEs.

Hypothesis 1: Extreme Weather has a negative impact on the sustainability of MSMEs. This hypothesis was supported with a path coefficient of 0.438, along with the t-statistic of 4.488, while the p-value was 0.000, proof that extreme weather disrupts operations, increases costs, and ultimately threatens to affect business sustainability. It implies the susceptibility of MSMEs to changes in the environment, which, in essence, requires resilience strategies among these businesses.

Hypothesis 2: Extreme Weather influences the adoption of Digital Adaptation Strategies for Environmental Risk Management. The path coefficient was highly significant at 0.964, with a t-statistic of 7.659 (p-value = 0.000), showing a strong positive relationship. The findings imply that extreme weather forces MSMEs to adopt digital solutions, such as IoT and GIS, in order to manage environmental risks and enhance operational efficiency.

Hypothesis 3: Digital adaptation strategies for the management of environmental risk positively affect the sustainability of MSMEs. This hypothesis was found to be true with a path coefficient of 0.552, t-statistic of 5.761, and p-value of 0.000. These results confirm that the adoption of digital technologies such as real-time monitoring and data analysis enhances the sustainability of MSMEs by managing risks better and maintaining continuity of operations during disasters.

Hypothesis 4: Digital adaptation strategies to environmental risk management mediate the relationship between Extreme Weather and sustainable MSMEs. In this regard, the indirect effect was significant, as indicated by a path coefficient of 0.532, with a t-statistic of 5.774 at a p-value of 0.000; thus, the mediating role of digital adaptation strategies was supported. This finding highlights that extreme weather directly impacts MSME sustainability but also indirectly influences the adoption of digital tools that could enable them to manage environmental risks more effectively.

This study elucidates the impact of extreme weather on the sustainability of MSMEs and the role of digital adaptation strategies for mitigating environmental risk. Previous study showed that extreme weather threatens MSME sustainability, with potential firm closures or significant debt, especially in climate-sensitive sectors such as agriculture and tourism (Schaer & Kuruppu, 2018). Prior studies have shown that climate-related events, such as floods and storms, significantly reduce business resilience, especially for MSMEs lacking adaptive capacity, while collaborative approaches, such as community-based initiatives for flood protection or resource sharing, can enhance adaptation efforts and help small businesses leverage collective resources for more effective measures (Nagy et al., 2023). In comparison, our findings suggest that MSMEs in emerging markets are even more challenged by the weakness of infrastructural support and financial constraints.

On the other hand, the findings show that extreme weather conditions significantly influence the adoption of digital adaptation strategies and further support previous studies that link environmental uncertainty with increased digital transformation (Chari & Novukela, 2023). For instance, IoT and GIS have been identified as good contributors to the enhancement of preparedness for disasters and business continuity for large enterprises (Vermiglio et al., 2022). Our study, however, shows that even resource-constrained MSMEs adopt digital strategies to manage environmental risks, so digitalization is increasingly regarded as a sort of necessary evil rather than just competitive advantage.

Moreover, the study confirms that digital adaptation strategies add to the positive contribution towards the sustainability of MSMEs, which supports previous literature on the role of digital resilience (Őri et al., 2024). Businesses that apply digital tools recover more effectively from climate-related disturbances since digitalization enhances operational flexibility and resource efficiency (Cheong et al., 2024). Our findings extend this understanding by showing that even small enterprises with limited technological resources can benefit from accessible digital solutions, such as mobile-based risk management systems.

This study makes a major contribution to the literature in identifying digital adaptation strategies as the mediating role between extreme weather and MSME sustainability. While extreme weather directly threatens business operations, it also encourages MSMEs to adopt digital tools that can help them manage environmental risks more effectively. This aligns with prior research that emphasizes a shift from reactive to proactive risk management through digitalization, where digital tools create interconnected systems that break down silos and enable organizations to assess the cross-functional impacts of potential threats (Sotamaa et al., 2024).

Theoretically, this study enriches the RBV by highlighting how digital capabilities act as strategic resources in promoting business resilience. Unlike other RBV applications that predominantly focus on financial or human capital, our findings extend the framework by placing digital adaptation at the core of MSMEs' sustainability.

In sum, this research underpins the essential drive of digital adaptation in mitigating adverse weather conditions on the sustainability of MSMEs. An integrated approach to environmental risk management and a digital orientation could certainly help MSMEs enhance their resilience for long-term business continuity. Further research along this crossroad is recommended, especially in countries with emerging economies where the development of

digital infrastructure and policies for climate adaptation are still lagging.

CONCLUSION

This study has shown that extreme weather conditions have a strong impact on the sustainability of MSMEs and, therefore, require particular adaptation strategies using digital tools. Practical applications of technologies like IoT and GIS in managing environmental risks can increase resilience.

IoT application can be managed by applying an IoT-enabled fleet management system using GPS and telematics for vehicle location tracking, traffic condition prediction, and optimization of routes. It allows the minimization of delays, saving in the consumption of fuel, and reduction in the operational disruptions caused by adverse weather conditions. IoT-based environmental monitoring sensors can be installed at the warehouses or manufacturing premises for real-time monitoring of temperature, humidity, and quality of air for stored goods and commodities, especially perishable ones, to ensure their safety. IoT-integrated supply chain management platforms would provide real-time inventory levels and shipment conditions updates, thereby enabling MSMEs to act in advance to prevent losses on account of climate events.

Secondly, GIS applies through spatial risk mapping tools that would analyze and visualize data on flood zones, landslide-prone areas, and other climate vulnerabilities. This map enables the MSME to strategically locate their operations, warehouses, or delivery routes within safer areas. GIS-based disaster response planning tools can further assist MSMEs by providing predictive weather patterns and real-time alerts, which would enable businesses to make appropriate schedule adjustments and resource allocation in the face of extreme weather. For instance, a GIS dashboard may combine real-time satellite imagery with historical weather data to help in logistics decision-making, thus reducing risks and ensuring continuity.

In implementing the above technologies, MSMEs should focus on more affordable IoT devices, such as low-cost GPS trackers, wireless environmental sensors, and cloud-based supply chain management platforms. Regarding GIS, open-source applications such as QGIS or public-private partnerships in government mapping agencies can reduce costs and generate essential spatial analytics.

The findings suggest that policymakers should provide concentrated support for MSMEs in the adoption of these technologies, including subsidies for IoT devices, grants for GIS-based risk mapping projects, and training programs to enhance technical skills among MSME owners. By applying IoT and GIS in these particular uses, MSMEs will be better positioned to adapt to environmental vulnerabilities and ensure their long-term sustainability and operational resilience.

REFERENCES

Alshahrani, R., Rizwan, A., Alomar, M. A., & Fotis, G. (2024). IoT-Based Sustainable Energy Solutions for Small and Medium Enterprises (SMEs). *Energies*, *17*(16). https://doi.org/10.3390/en17164144

Asian Development Bank (ADB). (2021). Digital Technologies for Climate Action, Disaster Resilience, and Environmental Sustainability. In *Orthopade* (Vol. 50, Issue October).

Browder, R. E., Dwyer, S. M., & Koch, H. (2024). Upgrading adaptation: How digital transformation promotes organizational resilience. *Strategic Entrepreneurship Journal*, *18*(1), 128–164. https://doi.org/10.1002/sej.1483

Chari, F., & Novukela, C. (2023). The influence of information and communication technologies on disaster relief operations: a case of Cyclone Idai in Zimbabwe. *Journal of Humanitarian Logistics and Supply Chain Management*, *13*(4), 399–409. https://doi.org/10.1108/JHLSCM-11-2021-0119

Cheong, T. S., Li, T., Shi, X., & Yu, J. (2024). Editorial: New directions of digital economy, energy transition, and climate change in the post-COVID-19 era: application of machine learning and other advanced analytical techniques. *Frontiers in Environmental Science*, *12*(November), 2023–2025. https://doi.org/10.3389/fenvs.2024.1514467

Dima, E. T. Y. D., Amaral, M. A. L., & Manehat, B. Y. (2023). Empowerment of msmes resilience with pestel the strategy to minimize economic poverty in East Nusa Tenggara province. *Enrichment : Journal of Management*, *13*(1), 435–442. https://doi.org/10.35335/enrichment.v13i1.1306

Ebi, K. L., Vanos, J., Baldwin, J. W., Bell, J. E., Hondula, D. M., Errett, N. A., Hayes, K., Reid, C. E., Saha, S., Spector, J., & Berry, P. (2020). Extreme Weather and Climate Change: Population Health and Health System Implications. *Annual Review of Public Health*, *42*, 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

Goktas, P., & Dirsehan, T. (2024). Using PLS-SEM and XAI for casual-predictive services marketing research. *Journal of Services Marketing*, *1*(July 2024), 53–68. https://doi.org/10.1108/JSM-10-2023-0377

Hauer, T. (2017). Education, Technological Determinism and New Media. *INTED2017 Proceedings*, *1*(2), 10026–10030. https://doi.org/10.21125/inted.2017.2401

IPCC. (2022). Cities, Settlements and Key Infrastructure. In *Climate Change 2022* –

Impacts, Adaptation and Vulnerability. https://doi.org/10.1017/9781009325844.008.907

Kurniawan, Maulana, A., & Iskandar, Y. (2023). The Effect of Technology Adaptation and Government Financial Support on Sustainable Performance of MSMEs during the COVID-19 Pandemic. *Cogent Business and Management*, *10*(1). https://doi.org/10.1080/23311975.2023.2177400

McPhearson, T., Karki, M., Herzog, C., Fink, H. S., Abbadie, L., Kremer, P., Clark, C. M., Palmer, M. I., Perini, K., & Dubbeling, M. (2018). Urban Ecosystems and Biodiversity. *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*, 257–318. https://doi.org/10.1017/9781316563878.015

Mora, L., Deakin, M., Zhang, X., Batty, M., de Jong, M., Santi, P., & Appio, F. P. (2021). Assembling Sustainable Smart City Transitions: An Interdisciplinary Theoretical Perspective. *Journal of Urban Technology*, *28*(1–2), 1–27. https://doi.org/10.1080/10630732.2020.1834831

Myanmar, S., Myanmar, E. H. S., Assessment, Q., Msmes, M., & Ehs, S. (2024). *Assessing and Promoting Sustainable Opportunities in Myanmar MSMEs*. *September*.

Nagy, G. J., Krishnapillai, M., Saroar, M., & Olivares-Aguilera, I. C. (2023). Editorial: Climate risks, resilience and adaptation in coastal systems. *Frontiers in Climate*, *4*. https://doi.org/10.3389/fclim.2022.1090577

Őri, D., Szabó, I., Kő, A., & Kovács, T. (2024). Digitalizing in crisis: the role of organizational resilience in SMEs' digitalization. *Journal of Enterprise Information Management*, *37*(4), 1185–1205. https://doi.org/10.1108/JEIM-03-2023-0141

Pandey, B., & Ghosh, A. (2023). Urban ecosystem services and climate change: a dynamic interplay. *Frontiers in Sustainable Cities*, *5*. https://doi.org/10.3389/frsc.2023.1281430

Ramanathan, V., Von Braun, J., Tiarv, D., & Dnvs, S. (2022). Resilience of People and Ecosystems under Climate Stress. In *Resilience of People and Ecosystems under Climate Stress* (Issue July).

Rusmayadi, G., Nofirman, & Fadhlihi, A. (2023). Climate Change Mitigation and Adaptation Strategies for Sustainable Resource Management. *West Science Journal Economic and Entrepreneurship*, *1*(03), 144–154. https://doi.org/10.58812/wsjee.v1i03.162

Schaer, C., & Kuruppu, N. (2018). Private-sector action in adaptation: Perspectives on the role of micro, small and medium size enterprises. In *UNEP DTU Partnership UN-City Copenhagen Marmorvej 51, 2100 Copenhagen Ø, Denmark http://www.unepdtu.org @unepdtu ISBN: 978-87-93458-28-4 Design* (Issue April).

Sitorus, F. J. philip, & Montana, F. V. (2023). Peningkatan Kualitas Pelayanan Kereta Komuter Berdasarkan Persepsi Pengguna Dengan Menggunakan Metode ServQual dan Zone of Tolerance: Studi Kasus Tanah Abang DKI Jakarta. *Widyakala Journal : Journal of Pembangunan Jaya University*, *10*(1). https://doi.org/10.36262/widyakala.v10i1.632

Sotamaa, T., Reiman, A., & Kauppila, O. (2024). Manufacturing SME risk management in the era of digitalisation and artificial intelligence: a systematic literature review. *Continuity & Resilience Review*. https://doi.org/10.1108/crr-12-2023-0022

Southwick, S. M., Bonanno, G. A., Masten, A. S., Panter-Brick, C., & Yehuda, R. (2014). Resilience definitions, theory, and challenges: Interdisciplinary perspectives. *European Journal of Psychotraumatology*, *5*, 1–14. https://doi.org/10.3402/ejpt.v5.25338

The Central People's Government of the People's Republic of China. (2022). National Climate Change Adaptation Strategy 2035. *Chinese Academy of Sciences*.

Tresna, I. C., & Sijabat, R. (2023). Analisis Pengaruh Digital Marketing, Brand Awareness dan Campus Facilities terhadap Enrollment Intention pada Sebuah Perguruan Tinggi Swasta. *Widyakala Journal : Journal of Pembangunan Jaya University*, *10*(2), 87. https://doi.org/10.36262/widyakala.v10i2.831

Vermiglio, C., Noto, G., Rodríguez Bolívar, M. P., & Zarone, V. (2022). Disaster management and emerging technologies: a performance-based perspective. *Meditari Accountancy Research*, *30*(4), 1093–1117. https://doi.org/10.1108/MEDAR-02-2021-1206

Wedawatta, G., Ingirige, B., Jones, K., & Proverbs, D. (2011). Extreme weather events and construction SMEs: Vulnerability, impacts, and responses. *Structural Survey*, *29*(2), 106–119. https://doi.org/10.1108/02630801111132795

World Economic Forum. (2024). *Innovation and Adaptation in the Climate Crisis: Technology for the New Normal*. *January*.

Yun, N. Y., & Ülkü, M. A. (2023). Sustainable Supply Chain Risk Management in a Climate-Changed World: Review of Extant Literature, Trend Analysis, and Guiding Framework for Future Research. *Sustainability (Switzerland)*, *15*(17). https://doi.org/10.3390/su151713199