MANKIND QUARTERLY Mankind Quarterly, 66(2), 243-277 2025 Winter Edition
ISSN: 0025-2344

Climate Change Sensitivity, Adaptive Capacity, and Technology Adoption: Implications for Farmers' Economic Well-Being in Malaysia's Muda River Basin

Nik Ahmad Sufian Burhan[*,†,‡,§] Hayrol Azril Mohamed Shaffril[*,¶] Suryani Darham[†]
Asnarulkhadi Abu Samah[‡,‖] Haliza Abdul Rahman[*]
Shaufique Fahmi Ahmad Sidique[*,+*] Samsul Farid Samsuddin[††] Nobaya Ahmad[†]
Jasmin Arif Shah[*,‡‡] Nurul Amiera Khalid[*] Abdul Rais Abdul Latiff[+†]
Liew Juneng[+‡] Fredolin Tangang[+‡,+§]

Abstract

The Muda River Basin (MRB), Malaysia's largest granary area, faces increasing climate extremes that threaten agricultural productivity and farmer livelihoods. Understanding how farmers perceive climate risks is critical for developing effective adaptation strategies. In this study, climate change sensitivity is defined as farmers' perception of economic, political, cultural, and institutional susceptibility to climate-related impacts. This study investigates how these dimensions of sensitivity influence adaptive capacity and technology adoption, and how these factors, in turn, affect economic well-being. Data were collected from 382 farmers across five districts in Kedah using a structured questionnaire, and analysed with partial least squares structural equation modelling (PLS-SEM). The findings show that both adaptive capacity ($\beta = .60$, $p < .01$) and technology adoption ($\beta = .18$, $p < .01$) significantly enhance economic well-being. Adaptive capacity was strongly shaped by all four sensitivity dimensions, while economic and cultural sensitivity also directly influenced technology adoption. Climate anxiety, included as a control variable, reduced both adaptive capacity and adoption rates. These results underscore the importance of institutional support and cultural considerations in strengthening farmers' adaptive responses. Policy measures that promote access to technology, build farmer trust in institutions, and integrate mental health awareness such as climate anxiety into extension programs can enhance resilience and improve economic well-being in the MRB.

Keywords: Economic wellbeing; Muda River Basin; Climate change sensitivity; Technology adoption; Adaptive capacity; Agricultural community

[*]Institute for Social Science Studies, Universiti Putra Malaysia, Selangor, Malaysia
[†]Department of Social and Development Sciences, Faculty of Human Ecology, Universiti Putra Malaysia, Selangor, Malaysia
[‡]Malaysian Community Development and Planning Association (MyCDA)
[§]Corresponding author, email: nikahmadsufian@upm.edu.my
[¶]Department of Social Science Education, Faculty of Social Sciences, Universitas Negeri Malang, Malang City, Indonesia
[‖]Malaysian Research Institute on Ageing, Universiti Putra Malaysia, Selangor, Malaysia
[+*]School of Business and Economics, Universiti Putra Malaysia, Selangor, Malaysia
[††]Department of Library and Information Science, Faculty of Art and Social Science, Universiti Malaya, Kuala Lumpur, Malaysia
[‡‡]Department of Agriculture Technology, Faculty of Agriculture, Universiti Putra Malaysia, Selangor, Malaysia
[+†]School of Social Sciences, Universiti Sains Malaysia, Minden, Malaysia
[+‡]Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Selangor, Malaysia
[+§]Faculty of Arts and Social Sciences, Universiti Brunei Darussalam, Brunei

1 Introduction

The Muda River is the longest river in Kedah, Malaysia, measuring 180 kilometres. It is critical for sustaining agriculture in the Muda River Basin (MRB) and water supply in the country's northern states. It is primarily used to water rice fields and move local fishing boats in the area surrounding its estuary (Abd Halim et al., 2018; Lee et al., 2013; Sim et al., 2018). In the last few decades, the area has experienced severe and drastic weather and climate conditions, including droughts caused by the El Niño phenomenon in 1997 and floods caused by the La Niña phenomenon in 2011/2012. Severe thunderstorms have also been known to occur on an annual basis, accompanied by windstorms, flash floods, and landslides. Monsoonal floods have also resulted in losses, including the deaths of people in other parts of the country affected by monsoon winds. The 2010 flood in Kedah was one of Malaysia's worst monsoon floods. It resulted in significant financial losses and increased pressure on the government's budget (Chan, 2014).

The MRB lies in Malaysia's humid tropical climate, with mean annual temperatures ranging from 26 to 28°C and annual rainfall between 2,160 and 3,000 mm, conditions that have long supported paddy farming. These stable climatic conditions, however, make the region especially sensitive to climate variability and warming (Tan et al., 2019; Zainal et al., 2014). Even a modest rise of 1 to 2°C can intensify the hydrological cycle, increase evapotranspiration, alter rainfall patterns, and elevate flood risks. Such changes directly threaten paddy farming, which relies heavily on predictable rainfall and stable water management systems. This illustrates the concept of climate sensitivity, where relatively small climatic shifts can trigger disproportionate impacts on agriculture and livelihoods.

The MRB's climate appears to have changed recently, with frequent occurrence of extreme weather conditions. Climate change continues to pose a significant threat to the basin as temperatures rise, precipitation patterns shift, and extreme weather events become more common (Luhaim et al., 2021). Droughts have also become more frequent and intense as a result of reduced rainfall, particularly during the southwest monsoon, and increased evapotranspiration caused by high temperatures. Droughts have the greatest impact on agriculture, and therefore the economy. For example, Alam et al. (2010b) discovered that increasing temperature and rainfall above the optimal level reduced paddy output. These crop yield reductions also reduce farmers' income, increasing the incidence of poverty and temporary unemployment (Alam et al., 2010a, 2012).

Climate change causes annual floods in the MRB, which is a major concern. Flooding is defined as the condition in which water from the river catchment area overflows and causes the river level to rise, resulting in floods (Hyndman & Hyndman, 2016). Ghani et al. (2010) reported in their work that flooding in the MRB catchment area is a recurring event during the rainy season, though the extent of the flooding varies from year to year. Flooding in 1988, 1998, and 2003 resulted in significant property and human loss, as well as a reduction in agricultural production. For example, a flood in October 2003 affected an estimated 45,000 people (Julien et al., 2006). According to Rehan et al. (2024) the wet planting season, which coincides with the northeast monsoon, is the most damaging for paddy farming due to flooding. This indicates the need to take precautions to avoid flooding. Floods also have a significant impact on rice yield, leading to fluctuations in food production and supply (Rehan et al., 2020). Sah et al. (2021) and Ercan et al. (2013) described the effects of climate change on Kedah's farmlands, with heavy rains being attributed to climate change. These rains have altered tide and sea levels, resulting in seawater intrusion and an impact on water and soil salinity.

While global sea levels have risen by approximately 10 cm over the past century and are projected to rise by about 30 cm by 2100 (IPCC, 2021), the inland geography of the MRB limits the direct effects of sea-level rise. Thus, concerns such as seawater intrusion are less relevant here than in coastal regions. However, farm production has been affected. According to Mei et al. (2020), floods pose a threat to fishing in the MRB because they are likely to affect fish stocks that are critical to the community's livelihood (Ghani et al., 2010; Omar et al., 2003). Although extreme weather events like floods and droughts are rare, their severity and impact on livelihoods necessitate attention. While attributing trends in their frequency directly to climate change remains challenging due to data limitations and natural variability, the consequences of such events for agricultural communities in the MRB justify their centrality in this study.

Climate change poses a threat to the MRB's agriculture sector due to episodes of drought and flood. Flooding and other forms of extreme weather reduce crop yields, present economic challenges, and make farmers' lives difficult. It has been established that these climatic conditions force farmers to devise strategies to increase their resilience and maintain their source of income, thereby involving also the government. Akhtar et al. (2019) discovered that farmers in Kedah who are more climate change resilient tend to have higher crop yields than those who are only moderately adapted to climate change.

This may reflect a broader pattern in which farmers who are able to adapt effectively to climate change also tend to manage other agricultural challenges more successfully, such as pest infestations and plant diseases, suggesting a general adaptive competence. This connection is plausible, as adaptive behaviour is often influenced by underlying traits such as problem-solving ability, risk perception, and access to resources. There are opportunities to improve extension services and government support for farmers by providing grants and training to increase flexibility and agricultural productivity.

Afroz et al. (2017) discovered in a survey that Malaysian rice farmers are increasingly willing to invest in crop insurance as a disaster coping mechanism, reflecting a farmer-led adaptation strategy. Such strategies also include adjusting practices, enhancing awareness, and using available resources to manage risks. At the same time, effective adaptation depends heavily on institutional and political support. This includes government-backed grants, training, and timely disaster response. As Chan (2014) points out, political and institutional factors, particularly the efficiency and timeliness of government action, play a critical role in shaping national capacity to manage climate-related hazards. Together, these farmer-led and institutional responses highlight the dual pathways of adaptation that underpin resilience in the MRB.

Building on this dual perspective, our study examines how climate change sensitivity influences farmers' adaptive capacity, technology adoption, and economic well-being in the MRB. It focuses on farmers' perceptions of economic, political, cultural, and institutional sensitivities, the four dimensions of the social system's sensitivity to climate change identified by Fenton et al. (2007) and Marshall et al. (2010). By analysing these perceptions, the study explores how they shape adaptive capacity and technology adoption, which in turn affect farmers' economic well-being. This study is distinctive because it looks into how farmers perceive the economic and cultural consequences of climate extremes, as well as the effectiveness of political systems and institutions in responding to these challenges from their perspective. Finally, this study predicted that these four dimensions of climate change sensitivity would have an impact on farmers' economic well-being by influencing their ability to adapt and adopt technology in response to changing climate conditions. Figure 1 depicts the hypothesized relationships between these variables, with adaptive capacity and technology adoption serving as mediators. They play an important role in mitigating the impact of climate change on the economic well-being of MRB farmers.

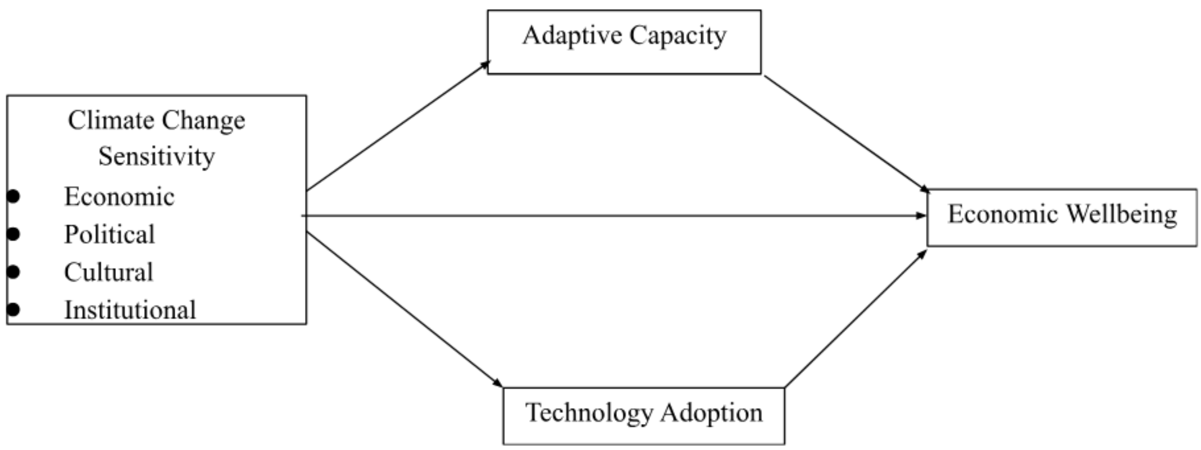

Figure 1: The hypothesised relationships between climate change sensitivity, adaptive capacity, technology adoption, and economic wellbeing. Source: Author's illustration.

This study sought to integrate Rational Choice Theory (RCT) by assuming that farmers, as rational individuals, would consider the available knowledge and options that would allow them to maximise their farming productivity and sustainability. These outcomes could be achieved through increased adaptability and technology adoption, as expected. Farmers are unlikely to change unless confronted with external forces, such as climate extremes, because improving adaptive capacity and adopting new technology, while beneficial, require effort and money. Thus, it cannot be ignored that farmers' willingness to cope with climate extremes is determined by a trigger factor known as climate change sensitivity. In this study, perceived sensitivities are viewed as sources of raising awareness, acquiring information, or knowledge about uncertainties. These factors may lead farmers to act, such as selecting strategies from the available choices or options, increasing efforts to become more adaptive, or adopting technology in responding to climate extremes in order to achieve optimal results in their agricultural or economic endeavours.

The remaining sections of this work are organised as follows: Section 2 discusses rational choice theory and farmers' responses to climate change. Section 3 describes the specific concepts and definitions for the variables used in this study. Section 4 discusses other studies that have been conducted to determine the relationship between climate change sensitivities, technology adoption, adaptive capacity, and economic wellbeing. Section 5 discusses the methodology, Section 6 presents the research findings, and Section 7 concludes.

2 Rational Choice Theory and farmers' adaptation to climate change

According to Rational Choice Theory (RCT), people make decisions based on the potential gain and loss associated with the available options in order to maximise their benefits. RCT could help farmers understand why they choose specific adaptive measures to improve their adaptive capacity to climate change. While farmers do not need to explicitly understand rational choice theory, their decision-making process can still align with its assumptions if they behave rationally in weighing options. The application of RCT to climate adaptation can shed light on the decision-making system that drives farmers' actions in response to climate change, which is critical given ongoing climate change superimposed on long-standing climate variability.

Farmers are rational people who are constantly looking for the best ways to maintain or improve their standard of living. Climate change has an impact on agriculture in a variety of ways, including crop production, pest and disease management, and irrigation water availability. Farmers must decide which of the following strategies to use to adapt to changing conditions: adopting technology, selecting new crop varieties, planting at different times, or investing in irrigation. According to RCT, individuals are generally expected to choose the strategy they believe will reduce costs while providing the greatest benefit. Therefore, RCT is best understood as a descriptive theory, as it helps explain how farmers actually make decisions in practice rather than prescribing how they should ideally decide. For example, a farmer may decide to use a drought-tolerant crop variety if the expected benefit (e.g., high yields during dry conditions) outweighs the cost. According to Deressa et al. (2009), factors influencing decision-making include the farmer's level of information, financial capacity, and social network. These factors help farmers evaluate the potential benefits of different adaptive measures.

RCT assumes that people understand the consequences of their decisions. However, when it comes to climate change, there is much uncertainty about the consequences of farmers' actions. The issue is that climate projections are frequently uncertain, and the viability of adaptive measures can vary depending on the context. However, this does not preclude the use of RCT because farmers' behaviour is influenced by their subjective perception of risks and uncertainties (Grothmann & Patt, 2005). As a result, farmers may choose to implement less risky measures such as crop rotation over more drastic measures such as changing the entire farming system. These decisions demonstrate a clear effort to maximise expected payoffs in risky conditions, which is a key tenet of RCT (Cinner et al., 2009). Farmers with access to better climate information or who have experienced previous climate events may be willing to accept high-cost strategies in exchange for higher long-term returns.

RCTs have primarily been used to explain decision-making by self-interested individuals, but social and institutional factors are equally important for climate adaptation. For example, social networks can provide farmers with valuable information about effective adaptive measures, lowering the costs of experimentation and increasing the perceived returns on various approaches (Adger et al., 2005b). Furthermore, the government and other institutions can help to reduce the costs of implementing adaptive measures by introducing new technologies or incentives such as subsidies or providing farmers with information on how to best proceed, all of which can influence farmers' cost-benefit analyses. Institutions can also create structures that promote or limit the development of adaptive capacity (Nkonya et al., 2015). In this way, RCT can be broadened to investigate how farmers reason about the costs and benefits of their climate change actions.

RCT can be used to assess farmers' technology adoption and adaptive capacity to climate change because it explains how and why certain actions are taken. RCT allows for a better understanding of why one adaptation strategy is preferred over another by taking into account the costs, benefits, risks and uncertainties that farmers face, as well as the social and institutional environment in which decisions are made. This approach emphasises the importance of providing farmers with adequate awareness and information, financial resources, and institutions to reduce the costs of adopting technology and adapting to climate change, thereby improving their ability to deal with climate extremes.

3 Definition of terms

This section provides definitions for the terms used in this work. It is difficult to define every concept or term in a way that is agreed upon by all scholars. The existing literature is used to develop conceptual definitions of economic well-being, adaptive capacity, technology adoption, and climate change sensitivity (economic, political, cultural, and institutional).

a) Economic well-being

Economic well-being refers to people's ability to cope with economic stressors, meet their needs and wants, plan for the future, and achieve financial security both now and in the future. This entails having enough financial resources to meet any type of economic challenge that one may face in life, attaining the required level of income that meets one's needs, ensuring that one has enough funds to meet his or her needs at any given time, saving for unforeseen incidences, managing one's finances in the right manner, and being able to sustain oneself financially in the event of job loss or even during the retirement period (Brou & Zeigler-Hill, 2020; Graham, 2011; Joo, 2008; OECD, 2013, 2020; Osberg, 2020; Stiglitz et al., 2009; Wilmarth, 2021; Yassin et al., 2015).

b) Adaptive capacity

Adaptive capacity refers to the ability of individuals, households, and communities to prepare for, cope with, and recover from the effects of climate change on their livelihoods and other socioeconomic activities. It addresses climate change preparedness, adaptability by employing new skills and strategies, financial and social stability, and community and extra-community support systems that reduce vulnerability to climate shocks (Adger et al., 2005a,b; Brooks et al., 2005; Engle, 2011; IPCC, 2007; Marshall et al., 2010; Nelson et al., 2007; Smit & Wandel, 2006; Yohe & Tol, 2002). This is essentially the same capacity needed to deal with past climate variability such as floods, droughts, and storms. Such events may become more frequent as the climate changes, although this is difficult to confirm due to limited data. The link between climate change and extreme events remains uncertain, and public debate is often influenced more by fear of change than by scientific evidence.

c) Technology adoption

Technology adoption refers to individuals' or organisations' willingness and capacity to adopt and use new agricultural technologies to mitigate the effects of climate change. This includes comprehending the competitiveness, compatibility, complexity, and tangibility of these technologies in improving the effectiveness and sustainability of agricultural management (Davis, 1989; Feder et al., 1985; Li et al., 2024; Rodríguez-Barillas et al., 2024; Rogers, 2003).

d) Sensitivity to climate change

Marshall et al. (2010) defined sensitivity in the context of climate change adaptation by the International Union for Conservation of Nature (IUCN) as the system's ability to effectively respond to climate change. The sensitivity of a social system to climate change is linked to economic, political, cultural, and institutional contexts, as described by Fenton et al. (2007) and Marshall et al. (2010). As a result, these factors can either exacerbate or mitigate the negative economic impact of climate change. According to Marshall et al. (2007), social systems based on a natural resource that is vulnerable to climate change will be more sensitive to its effects. When developing a climate change adaptation plan, it is necessary to assess the extent to which local people and resources are exposed to climate change. Scholars such as Marshall et al. (2010) and Fenton et al. (2007) believe that the sensitivity of the social system is determined by the economic, political, cultural, and institutional contexts.

- *Economic sensitivity*

Economic sensitivity to climate change refers to how people perceive climate change's impact on their income, financial security, sources of living, cost of living, employment, job security, business, and the overall economy. It considers the adaptation costs, likely economic impacts, and gains from adaptation measures (IPCC, 2007; O'Brien & Leichenko, 2000; Stern, 2007; Tol, 2009; World Bank, 2010).

- *Political sensitivity*

Political sensitivity to climate change refers to people's perceptions of the political system's ability and effectiveness in dealing with climate change. It includes perceptions of political willingness, the impact of political systems on strategies for mitigation and adaptation, the effects on political systems, and participation in decision making and lobbying for good policies (Adger et al., 2013b; Barnett & Adger, 2007; Buhaug, 2010; Gemenne et al., 2014; McCright & Dunlap, 2011).

- *Cultural sensitivity*

Cultural sensitivity to climate change is defined as people's perceptions of how climate change affects cultural systems and norms, beliefs and practices, and thus cultural heritage and social fabric. The development of adaptation and response to climate change focusses on cultural heritage, traditional ecological knowledge, and community identity (Adger et al., 2013a; Berkes et al., 2000; Crate & Nuttall, 2016; Ford et al., 2006).

- *Institutional sensitivity*

Institutional sensitivity to climate change is defined as people's perceptions of the ability and willingness of relevant institutions or organisations to respond to climate change. This entails the ability of these institutions to put in place measures that can be used in the implementation of climate change policies, as well as to support adaptation, mitigation, and resource management (Biermann et al., 2009; Gupta et al., 2010; Ostrom, 2010; World Bank, 2010; Young et al., 2008).

4 Literature review

Climate change gradually forces farmers to change their strategies in order to ensure sustainability and manage economic resources. Technology adoption and adaptive capacity play a significant role in determining farmers' ability to deal with such challenges.

4.1 Adaptive capacity and technology adoption promote farmers' economic well-being

The use of technology in agriculture significantly increases productivity and effectiveness: efficient farming tools, water-saving irrigation systems, and genetically modified crops. For example, using GPS-enabled tractors and remote sensing improves resource efficiency and productivity (Sishodia et al., 2020; Soussi et al., 2024), and drip irrigation increases water use efficiency and crop yield while lowering costs. Some crop varieties are genetically modified to be less susceptible to pests and diseases, increasing yield (ISAAA, 2017). Technological advancement also reduces production costs. Mechanisation and automation, such as automated harvesters, reduce labour costs and therefore production costs, which is critical in areas with a workforce shortage (Yoshida et al., 2022). Furthermore, technology integration in supply chain management reduces losses after the farm gate and transportation costs, thereby increasing returns (Sonka et al., 2023).

Improved technology promotes marketers and expands farmers' market access. E-commerce platforms and digital marketing tools improve market visibility and revenue generation (Lemma et al., 2018). Blockchain technology improves supply chain assessment and accountability, meeting consumers' demand for sustainable products (Azevedo et al., 2023). Improved market access can help farmers earn more money and potentially create a steady income. Technology can also help with agricultural risk management and climate change resilience. Accurate weather forecasting systems and climate models help farmers decide when to plant and harvest to avoid storms or extreme weather conditions (Challinor et al., 2018). Crop insurance and risk management technologies are additional measures that help farmers deal with financial risks associated with crop losses and price fluctuations (Velandia et al., 2009).

Adaptive capacity refers to the farmer's ability to adjust to new conditions and ways of working, and thus adopt new practices. Flexibility, creativity, and the ability to learn and use technology are key indicators of high adaptive potential. Farmers with high adaptive capacity are better positioned to experiment with new technologies and practices, resulting in higher productivity and thus higher economic returns. For example, conservation tillage can improve soil health and reduce erosion, potentially increasing the long-term return on investment (Cafer & Rikoon, 2018; Rizzo et al., 2024). The availability of resources and support systems is one of the most important factors influencing adaptive capacity. This implies that farmers who have good access to financial services, extension services, and technical support will be better positioned to adopt and benefit from new technologies. Subsidies and low interest rates can help farmers overcome technological and innovation barriers. Extension services and technical training programs provide the knowledge and skills required to implement new technologies (Davis et al., 2012).

Social networks and collaboration also improve adaptive capacity. Farmers who have strong social networks can share information, knowledge and resources, thereby increasing the adoption of new methods and technologies. Farmer cooperatives and associations are examples of community-based approaches for promoting group-based climate change adaptation (Wigboldus et al., 2016). These networks encourage knowledge sharing and problem solving. This improves farmers' ability to deal with shocks and stresses, as well as their overall economic situation. To build strong adaptive capacity, it is also necessary to have strong institutional and policy support. Policies such as R&D incentives, financial incentives, and technology promotion can significantly improve farmers' adaptive capacity (Nelson et al., 2010). Climate change-friendly policies that fund research into climate-friendly crops and technology can eventually provide farmers with the necessary tools to deal with climate change. Land tenure and property rights should allow farmers to invest for the long term and adopt new technologies.

The use of technology and the development of adaptive capacity have an impact on the farmer's income, stability, and growth. Technological advancement can increase productivity and lower the costs, allowing for higher income (Shi et al., 2023). For example, precision agriculture technologies can be used to increase production while lowering production costs, thereby increasing farmers' net income (Shofiyati et al., 2024). Furthermore, adaptive capacity assists farmers in dealing with climate and market risks and uncertainties, thereby protecting their income from natural disasters and market fluctuations. Technology adoption and adaptive capacity also contribute to the long-term viability of farm businesses, resulting in increased farm productivity over time.

Furthermore, the factors that influence technology adoption and adaptive capacity have an impact on equity and inclusion. Smallholders can close the gap with large-scale farmers by leveraging information and communication technologies, as well as flexible inputs and services (Harvey et al., 2018). Inclusionary policies and support systems for excluded groups are a good example of how to promote equitable rural development by improving their adaptive capacity and economic well-being. Technology adoption and adaptation capacity are viewed as critical in increasing farmer income in the context of climate change. These characteristics contribute to higher productivity, lower costs, and better risk management, which helps to raise income per head while also potentially increasing the economy's vulnerability by creating greater dependence on external inputs, technologies, and market conditions. These are some of the factors that must be addressed in order to ensure that all farmers benefit from such improvements. Thus, climate change will have an impact on agriculture. By encouraging the use of technology and improving farmers' adaptive capacity, it will be critical for their economic well-being and agriculture's sustainability.

4.2 How does climate change sensitivity increase technology adoption?

To encourage farmers to adopt new technology during climate extremes, economic, political, cultural, and institutional sensitivity must first be established. All sensitivities influence farmers' adoption of technologies, supporting the concept of targeted strategies. These are some of the challenges that, if well addressed by policymakers and implementers, could lead to the development of good programs enabling farmers to adopt technology that improves their resilience to climate change.

4.2.1 Climate change's economic sensitivity and technology adoption

Economic sensitivity to climate change is defined as the extent to which climate variability affects farmers' economic condition, income, and stability. When farmers suffer significant economic losses as a result of natural disasters such as droughts, floods or heat waves, they face financial difficulties and look for ways to cope, which may include using new technologies. First, the economic consequences of climate extremes can encourage farmers to use technology to reduce potential damage and increase output. Those who have been affected by adverse weather and have suffered significant losses will be willing to invest more in technologies that can increase crop yields and/or reduce risk (Harvey et al., 2018). Drought-resistant crops, efficient irrigation methods, and improved weather forecasting methods are among the measures that could help prevent such losses (Frimpong et al., 2023; Khatun et al., 2021).

Furthermore, during times of economic stress, farmers are more likely to adopt technologies that promise short-term returns or cost savings, even if they require an investment. Similarly, financial incentives such as subsidies or grants may increase stakeholders' willingness to adopt new measures (Wu et al., 2022). Farmers who anticipate high returns from new technology are more likely to invest, particularly in areas where they have previously suffered economic losses due to climate change (Wang et al., 2019). As a result, the economic returns that can be realised from new technologies are very important in encouraging farmers to adopt them, especially after farmers experienced adverse economic impacts due to climate extremes.

4.2.2 Climate change's political sensitivity and technology adoption

Political sensitivity to climate change is another important factor in farmers' decision-making regarding technology ad

option. Government policies and laws can influence whether or not farmers embrace new technologies. Other policies, such as providing subsidies for climate-smart technologies or funding agricultural research, have been shown to improve farmers' ability to innovate. Climate-smart technologies may include tools that help farmers adapt to climate change, such as improved drainage systems to reduce flood risk. Political instability or adverse policy changes, for example, can create uncertainty and discourage investment in new technologies (Aisen & Veiga, 2013; Bertin et al., 2016).

The level of political sensitivity determines farmers' trust in the government and their willingness to accept new technologies. A positive perception of government climate change and agricultural modernisation plans can boost farmer confidence and technology adoption (Zakaria et al., 2020). On the contrary, if farmers believe that political leaders have abandoned them or are not providing the necessary support, they may be resistant to the adoption of new technologies (Crentsil et al., 2020). Furthermore, political sensitivity influences farmers' risk perception and willingness to use new technologies in their farming operations. Unfortunately, government policies and guidelines on climate change, which often provide farmers with guidance on how to approach climate change and technology as a viable means of managing and controlling it, are frequently met with political instability, making farmers hesitant to adopt new technologies (Hebsale Mallappa & Pathak, 2023; Wu et al., 2023). Such hesitation may arise from controversies among political elites or from a disconnect between farmers and policymakers, especially when farmers perceive government projects as ineffective or potentially harmful to their livelihoods.

4.2.3 Climate change's cultural sensitivity and technology adoption

Climate extremes are known to have a wide range of effects on people's social relationships, cultural norms, and beliefs, so cultural sensitivity is essential in the analysis. Cultural beliefs and practices shape farmers' attitudes towards new technologies and have a significant impact on their attitudes towards the adoption of new technologies, considering that some new technologies disrupt cultural norms and beliefs. People in agricultural societies may be sceptical of innovations that differ from traditional approaches (Shen et al., 2023). For example, technologies that require changes in farming practices may be rejected if they are perceived to violate people's beliefs or knowledge systems (Mohan et al., 2021). While this can be seen as an impediment, some scholars argue for the revival of indigenous knowledge systems to address problems that may not be easily solved with modern technologies. Traditional knowledge remains valuable for challenges that communities have long experienced, but it can also limit adaptation when new problems arise that require different solutions. In the case of climate change, we are not facing an entirely new issue, but rather an intensification of existing variability, which now demands greater attention than in the past.

However, new technologies can be embraced when they complement or improve culture. Technologies that improve or replace traditional practices, or that incorporate indigenous knowledge in their implementation, are more likely to be adopted (Denashurya et al., 2023). As a result, cultural consideration in these technologies may aid in their adoption and use (Adade Williams et al., 2020). Furthermore, cultural factors influence how technology is communicated and marketed. For cultures with high levels of communality, community-based strategies such as demonstrations or peer teaching can be more effective than individualistic approaches (Dutta, 2007). Involving local leaders and incorporating culture into the design and implementation of technology interventions has the potential to increase adoption (Questa et al., 2020).

4.2.4 Climate change's institutional sensitivity and technology adoption

Institutional sensitivity refers to farmers' awareness and attitudes towards institutional capability in dealing with climate change. The efficiency and level of support provided by these institutions have a significant impact on farmers' willingness to adopt new technologies. Institutions are important for technology adoption because they provide resources, information, and support. An example are agricultural extension services that train farmers to use new technologies effectively (Makate, 2020). Similarly, institutional support through the dissemination of research and technologies can encourage farmers to adopt new technologies (Schut et al., 2016).

Institutional credibility and reliability also influence farmers' perceptions. Fan et al. (2023) found that positive experiences with credible and effective institutions increase the likelihood that promoted technologies will be adopted. Unfavourable attitudes towards institutions, on the other hand, may reduce their eagerness to adopt new technologies (Cafer & Rikoon, 2018). Institutional support in the form of loans and/or grants from financial institutions can help farmers invest in new technologies (Geng et al., 2024). Such institutional supports are critical in providing assistance to farmers and facilitating technology adoption.

4.3 How does climate change sensitivity enhance adaptive capacity?

Sensitivities in the economic, political, cultural, and institutional domains can activate the required adaptive capacities. It is critical to understand how these domains can be effectively used to support adaptation and mitigate the effects of climate change. This section investigates how economic, political, cultural, and institutional sensitivity each can enhance an individual's ability to cope with climate change.

4.3.1 Climate change's economic sensitivity and adaptive capacity

Economic sensitivity refers to the assessment of the economic consequences of climate extremes on an individual or collective basis. It boosts adaptive capacity by encouraging preventive measures and investments such as insurance, diversification of income sources, or the use of sustainable practices (Adger, 2000). Furthermore, evidence suggests that as economic risks become more widely recognised, climate bonds and green investments emerge (Henderson et al., 2016).

Furthermore, economic sensitivity promotes risk culture, resulting in the development of technologies and strategies that reduce vulnerability, such as drought-tolerant crops and energy-efficient buildings (Pelling & High, 2005). This emphasis on economic resilience enables individuals and institutions to prepare for, respond to, and recover from climate shocks (Tol et al., 2008). Similarly, economic sensitivity encourages collaboration among various interested parties, such as governments, businesses, and civil society, for resource sharing, which is critical in the development of effective adaptation strategies (Agrawal, 2010). Climate change mitigation and adaptation can be accomplished through public-private partnerships, which can aid in the construction of infrastructure that can shield communities and enhance their resilience (Sovacool et al., 2015).

4.3.2 Climate change's political sensitivity and adaptive capacity

Political sensitivity to climate change entails an understanding of how politics and policies can mitigate the effects of climate change and thus strengthen a community's ability to respond to those impacts. This consciousness increases political participation and support for interventions like community-based adaptation strategies and policies (O'Brien et al., 2010). This is especially true where people believe their leaders are concerned about climate change (Adger et al., 2005a, 2005b).

Political sensitivity also influences resource allocation and governance effectiveness in managing climate change risks, emphasising the importance of political intervention in climate adaptation and government coordination in climate risk management (Pelling, 2010). As a result, good leadership is required to implement policies that benefit vulnerable groups while also promoting long-term development. Political sensitivity increases the likelihood of governments being accountable and transparent in the climate governance process. People and communities who are aware of the issues can challenge their leaders and their decisions, forcing policy changes that will improve and accelerate adaptation (Bulkeley & Betsill, 2013). This contributes to the development of a more sensitive and equitable framework for climate adaptation, thereby improving society's overall adaptive capacity (Pelling, 2010).

4.3.3 Climate change's cultural sensitivity and adaptive capacity

Climate change's cultural sensitivity refers to the way extreme weather events affect cultural beliefs, practices, and attitudes. This sensitivity improves adaptive capacity by integrating traditional knowledge with adaptive procedural strategies (Adger et al., 2013a). Local farmers have a wealth of knowledge about their surroundings as well as lessons learnt from previous challenges, which will be useful for today's adjustment (Turner & Clifton, 2009).

Cultural sensitivity can lead to the social integration and cooperation needed for adaptation. Understanding the cultural aspects of climate change helps sectors work together to address these issues (Adger, 2006). Well-knit networks make resources more available and increase people's collective capacity to cope with climate change (Pelling & High, 2005; Tompkins & Adger, 2004). Furthermore, cultural consciousness plays an important role in the stewardship and transfer of cultural inheritances when faced with climate change. Thus, cultural assets help communities identify tangible steps that should be taken to protect their culture (Cruikshank, 2001). This not only preserves cultural assets, but also fosters cultural and psychological attachment to the place and motivates adaptive interventions (Adger et al., 2013b; O'Brien et al., 2009).

4.3.4 Climate change's institutional sensitivity and adaptive capacity

Institutional sensitivity to climate change refers to people's perceptions of institutions' preparedness and ability to manage climate risks (Adger et al., 2005a,b). Higher levels of institutional sensitivity build trust in institutions and encourage collaboration with related agencies, which in turn contributes to climate risk mitigation and increases adaptive capacity (Gupta et al., 2010). In the Malaysian context, agencies such as the Department of Agriculture (DOA) and the Muda Agricultural Development Authority (MADA) play a central role in providing technical guidance, irrigation management, subsidies, and training to farmers in the MRB. The extent to which farmers perceive these institutions as responsive and reliable shapes their willingness to adopt recommended practices and technologies.

Communities and organisations that comprehend the diverse sectors engaged in the climate change process are more effectively equipped to improve adaptive practices. They are typically involved in resource distribution, research funding, and the creation of environments conducive to learning and adaptive management (Agrawal, 2010; Eakin & Lemos, 2006). Furthermore, incorporating cultural diversity into planning improves the comprehensiveness and implementation of adaptation measures, which are more likely to consider the needs of all segments of society, particularly vulnerable groups, and to be sustainable long-term. This approach further improves the ability to deliver adaptation and the community's readiness and recovery from climate impacts (Folke et al., 2005; Adger et al., 2005a,b).

5 Methods

This section describes the study's location, the main and control variables used in the study, as well as the validity and reliability of the instrument. It also outlines the methods for data collection and analysis.

5.1 Study location

This study included farming communities in the Muda River Basin (MRB). The MRB is a major river system in northwest Peninsular Malaysia, covering an area of 4,210 km^2 (Luhaim et al., 2021) (Figure 2). The river marks the border between Kedah and Penang, beginning in the Kedah mountain ranges and flowing about 30 kilometres south. The basin spans 180 kilometres and includes five districts involved in the current study: Baling, Kuala Muda, Kulim (Kuala Ketil), Padang Terap, and Sik (Daud & Safiei, 2018; Ghani et al., 2010; Julien et al., 2006).

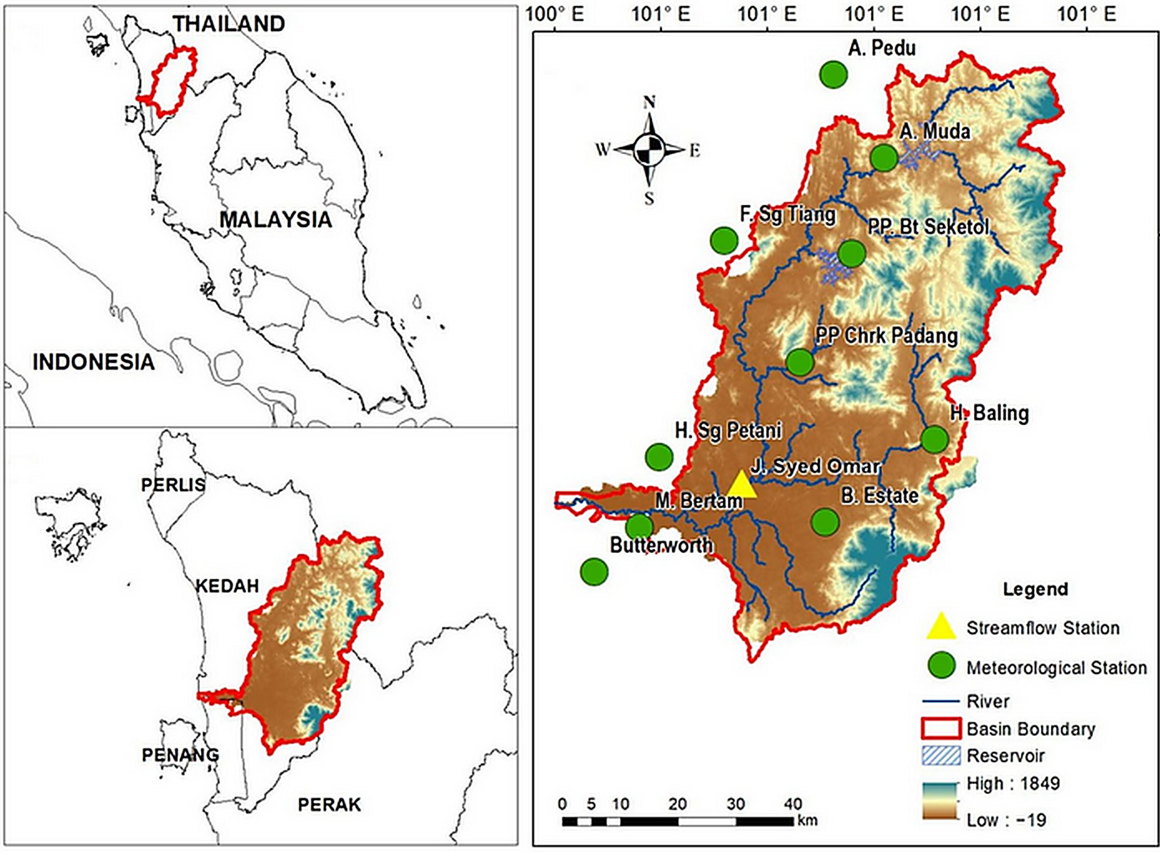

Figure 2: The Muda River Basin, situated in the northwest of Peninsular Malaysia. Map data sources: Malaysian Meteorological Department (MMD).

5.2 Survey instrument

This study took a survey approach, collecting data on the factors under investigation from respondents through questionnaires. The questionnaire was written in Malay. The instrument consisted of two primary components. The first section contains the respondents' basic demographic information. The instrument's second section includes a number of items used to assess the variables or study constructs. The construct-related items were developed by the researchers or adapted from earlier research to suit the rural and agricultural population being studied.

5.3 Variables and measures

The key variables or main constructs used in this study are: economic well-being, adaptive capacity, technology adoption, economic sensitivity, political sensitivity, cultural sensitivity, and institutional sensitivity. These constructs are created using a number of items, which are then rated on a Likert type scale of 1-5, with 1 representing 'strongly disagree' and 5 representing 'strongly agree'.

5.3.1 Economic wellbeing

Economic wellbeing was adapted from Yassin et al. (2015), who developed a scale of economic wellbeing and financial health that includes several aspects of an individual's economic status within the context of Malaysian society. The current study includes eight items that investigate how current or expected economic or financial stress affects the respondent's household income and savings, visionary spending, coping with emergency needs, living comfortably, spare expenditure for non-necessities such as travel, and security for retirement and during joblessness. A higher score on the five-point Likert scale indicates better economic well-being for the respondent. Two examples are:

- "I am satisfied with the household income." (In Malay: *"Saya berpuas hati dengan pendapatan isi rumah."*)
- "I have enough savings to cover emergency expenses." (In Malay: *"Saya mempunyai simpanan yang mencukupi untuk menampung perbelanjaan kecemasan."*)

5.3.2 Adaptive capacity

This study adapted Shaffril et al.'s (2013, 2017) measure of the social system's adaptation to climate change, which was developed based on Marshall et al.'s (2010) sixteen domains of individual adaptive capacity. This resulted in the development of 36 items that cover the sixteen aspects of climate change social adaptation. A higher score on the five-point Likert scale indicates a respondent's greater adaptive capacity. This includes an individual respondent's ability to anticipate, plan for, and deal with the increasing severity of climate extremes by leveraging current knowledge, skills, community support, social network, financial stability, skills, and willingness to learn and adapt while seeking new opportunities for sustainable livelihoods in the face of climate change. The items used for the construct include the following three examples:

- Domain 2 – Ability to cope with change: "Extreme weather doesn't stop me from going out to work." (In Malay: *"Cuaca melampau tidak menghalang saya daripada keluar bekerja."*)
- Domain 9 – Business size and approach: "I seek advice from experts in making decisions about my business." (In Malay: *"Saya mendapatkan nasihat daripada pakar dalam membuat keputusan berkenaan bidang usaha saya."*)
- Domain 11 – Income diversity: "I also do additional work apart from my current business to cover family expenses." (In Malay: *"Saya juga melakukan kerja tambahan selain daripada bidang usaha sekarang untuk menampung perbelanjaan keluarga."*)

5.3.3 Technology adoption

Rogers's (2003) Innovation Diffusion Theory (IDT) inspired the creation of a set of twenty items for the technology adoption construct. This framework identifies the five perceived characteristics of how innovations spread in society: relative advantage, compatibility, complexity, trialability, and observability. In this study, four items for each of these domains were created. Many previous studies have used similar items to assess technology adoption (e.g., Atkinson, 2007; Emani et al., 2018; Sattler & Nagel, 2010; Sharifzadeh et al., 2017; Yuen et al., 2021). Higher scores on the five-point Likert scale indicate greater technology adoption. Three examples of items used for the construct are provided below:

- Domain 1 – Relative advantage: "The agriculture technology shortens my time required for farming chores." (In Malay: *"Teknologi pertanian memendekkan masa yang saya perlukan untuk kerja-kerja pertanian"*)
- Domain 3 – Complexity: "I find it easy to learn how to use agriculture technology" (In Malay: *"Saya rasa mudah untuk belajar menggunakan teknologi pertanian"*)
- Domain 5 – Observability: "I can see improvements in farm productivity due to the technology." (In Malay: *"Saya dapat melihat peningkatan dalam produktiviti pertanian disebabkan oleh teknologi"*)

5.3.4 Climate change sensitivity

Economic, cultural, political, and institutional sensitivities were assessed using conceptual frameworks developed by Fenton et al. (2007) and Marshall et al. (2010). In the current study, thirty items representing these four constructs were developed to measure the degree to which farmers perceive that climate change has impacted their economy (9 items) and sociocultural practices (7 items), as well as the capacity and responsiveness of the political system (7 items) and relevant institutions (7 items) in dealing with climate change. A higher score on the five-point Likert scale indicates a greater intensity of climate change sensitivity, implying that respondents believe they are more affected (economically and culturally) by extreme weather, and that politicians and relevant institutions are more responsive in addressing climate change impacts. Here are four examples of items used for the four categories of sensitivity:

- ***Economic sensitivity***: "Extreme weather has disrupted productivity in my agricultural work." (In Malay: *"Cuaca yang melampau telah mengganggu produktiviti dalam kerja pertanian saya."*)
- ***Political sensitivity***: "Extreme weather occurrences cause politicians or community representatives to respond quickly to provide aid to the affected people or farmers." (In Malay: *"Kejadian cuaca yang melampau menyebabkan ahli politik atau wakil masyarakat bertindak balas dengan cepat untuk memberikan bantuan kepada ahli komuniti atau petani yang terjejas."*)
- ***Cultural sensitivity***: "Due to extreme weather, I rarely leave the house to attend public events in the village or surrounding area." (In Malay: *"Oleh kerana cuaca melampau, saya jarang keluar rumah untuk menghadiri majlis keramaian di kampung atau sekitar."*)
- ***Institutional sensitivity***: "In the current extreme weather conditions, government agencies assist farmers and residents in increasing or diversifying their sources of income." (In Malay: *"Dalam keadaan cuaca yang melampau sekarang, agensi kerajaan membantu petani dan penduduk dalam meningkatkan atau mempelbagaikan sumber pendapatan mereka."*)

5.3.5 Control variables

This study used five control variables: respondents' income, gender, age, perceived climate severity, and health adversity.

- ***Income.*** The respondents' income was assessed by asking for the exact amount of monthly income (Malaysian Ringgit) they received. The results were then logarithmically transformed with a base of ten.
- ***Female.*** The variable 'female' denotes the respondent's gender. For inferential data analysis, males are coded 1 and females are coded 2.
- ***Age.*** Respondent's age in years.
- ***Climate severity.*** An individual's perception of 'climate severity' typically refers to their subjective assessment of the severity or intensity of climate-related changes in their immediate surroundings. This was measured on a 10-point Likert scale (1 - strongly disagree, 10 - strongly agree) for the following statement: "The weather patterns in my area are quite extreme, with erratic and alarming occurrences of both rainfall and heat events." (In Malay: *"Corak cuaca di kawasan saya agak melampau, dengan kejadian hujan dan panas yang tidak menentu dan membimbangkan."*). A higher score from a respondent indicates that this person is more concerned or alarmed about climate extremes in their area, which includes fluctuating and unpredictable weather patterns as well as rain and heat occurrences.

- ***Health adversity.*** This study used a 10-point Likert scale (1-strongly disagree to 10-strongly agree) to elicit respondents' perceptions of the negative effects of climate extremes on their health status: "The extreme weather has adversely affected my health." (In Malay: *"Cuaca yang melampau telah menjejaskan kesihatan saya."*). Respondents with higher scores indicate that the severe weather has a significant impact on their health.

5.4 Validity and reliability

This study used expert validation to evaluate the items used in measuring the components of the research instrument. Appointed experts in climate change, agricultural extension, and agricultural economics have specifically verified the research instrument used in this study. Furthermore, to ensure the validity of the questionnaire, this study pre-tested it on 100 respondents. Cronbach alpha values for all constructs in the pilot test exceeded 0.75, including economic well-being (0.82), adaptive capacity (0.87), technology adoption (0.91), economic sensitivity (0.90), political sensitivity (0.79), cultural sensitivity (0.87), and institutional sensitivity (0.89). This demonstrates that the items in this study are valid in their respective construct measurements because they produce nearly the same numerical or score value each time they are used, assuming that all other conditions are equal, as stated by Hays and Revicki (2005).

5.5 Sample and data collection

Data were collected using a non-probability sampling method known as homogeneous convenience sampling. This approach was chosen because it can identify sub-groups of people who share certain characteristics, cultures, or occupations and rely primarily on agriculture for their income. Homogenous convenience sampling selects a population under study based on specific sociodemographic characteristics. In a study by Jager et al. (2017), the authors stated that, while probability samples provide more generalisable data, there are specific benefits to using non-probability convenience samples, particularly homogeneous convenience sampling. They are inexpensive, time-saving, simple to use, and faster than probability sampling techniques. Jager et al. noted that selecting convenience samples based on specific criteria can improve generalisability. This study contends that the research context, which consists of agricultural communities in the MRB, broadens this homogeneity and thus increases generalisability of the results. Because all respondents are exposed to the same environmental factors that are typical for the basin, particularly the impact of climate change, one could argue that the discovered tendencies apply to the entire population of agriculture communities in the MRB.

This study employed convenience sampling, in which respondents, primarily farmers, were identified on their farms and in social settings in towns. This made it simple to identify and mobilise a diverse group of farmers in the MRB and its various districts where they farm. Participants were recruited between May 20 and August 7, 2024. The enumerators were responsible for administering questionnaires during the survey, and participation was entirely voluntary. All participants were at least 18 years of age. Informed written consent was obtained from all participants prior to their inclusion in the study. The participants were fully informed of the study's purpose and how the data would be used, and the data was only to be used for research purposes in order to protect the participants' identities. For data protection purposes, all collected data were de-identified, with sample identifying information stored and handled in accordance with institutional data protection guidelines.

The study's power analysis was performed using G-Power software version 3.1.9.4, with the sample size formula from Faul et al. (2007). The number of participants required under convenience sampling was determined accounting for the number of independent variables, the average estimated effect size of the predictors (f^2), the alpha probability error (α), and the power (1 - β error probability). Power analysis revealed that for the current study, a minimum of 178 participants would be required to achieve an effect size of $f^2 = 0.15$, with 11 predictor variables (including control variables), a statistical significance level of .05, and a statistical power of .95. To improve the sensitivity of the results, the alpha level of significance was increased from .05 to .01 and the statistical power from .95 to .99. As a result, the G-Power software recommended a new minimum sample size of 287 respondents to achieve statistical power of 99%.

6 Results

This section includes the results for both the measurement and structural models. The primary goal is to ensure the constructs and items in this study are reliable and valid. The structural model assessment determines the direct and indirect effects of the variables specified in the path model.

6.1 Descriptive analysis

The data for this study were collected from 382 farmer respondents, 346 males and 36 females, all of whom living in MRB's agricultural settlements. Table 1 shows the variables used in this study, along with the basic characteristics of the respondents. The mean age of these farmers is likely higher than the national average for the working population in Malaysia. However, it is not as high as what is often observed in other developing countries, where younger generations tend to leave agriculture and the nation becomes increasingly reliant on food imports.

Mean scores on the 1 to 5 Likert scale were 2.98 for economic wellbeing, 3.69 for technology adoption, and 3.28 for adaptive capacity. Economic sensitivity was the highest of the four measures of sensitivity, at 3.48, followed by political sensitivity (3.14), institutional sensitivity (2.54), and cultural sensitivity (2.01). Perceived climatic severity was very high (8.18 on a Likert scale of 1 to 10), whereas perceived health adversity was low (3.97).

Table 1: Descriptive statistics for all variables.

Measurement scale	Variable	Mean	Standard deviation
Likert Scale 1 – 5	Economic wellbeing	2.98	0.68
	Economic sensitivity	3.48	0.55
	Political sensitivity	3.14	0.63
	Cultural sensitivity	2.01	0.64
	Institutional sensitivity	2.54	0.60
	Adaptive capacity	3.28	0.56
	Technology adoption	3.69	0.73
Likert Scale 1 – 10	Climate severity	8.18	1.45
	Health adversity	3.97	2.22
Total income (RM per month)		2353	1984
Age (years)		48.94	14.64

6.2 Results for the measurement model

This study sought to identify the mediating roles of adaptive capacity and technology adoption in the relationship between climate change sensitivity and farmers' economic well-being. Hair et al. (2022), Ringle et al. (2024), and Henseler et al. (2015) recommended that the measurement model be evaluated using 1) convergent validity and reliability, and 2) discriminant validity using the HTMT ratio.

6.2.1 Convergent validity and reliability

Table 2 shows the average variance extracted (AVE), composite reliability (CR), and Cronbach's alpha (CA) scores for all seven components examined in this study. The first step in evaluating reflective measurement models is to determine the reliability of the indicators. According to Hair et al. (2022) and Malhotra (2010), an outer loading or factor loading above .71 indicates that the construct explains more than 50% of the indicator's variance ($0.71^2 = 0.5$), indicating acceptable reliability. However, Hair et al. (2019, 2022) advised against eliminating items with outer loadings less than 0.70 but greater than 0.40, particularly if the deletion did not result in an increase in composite reliability (CR) and average variance extracted (AVE).

Table 2: Convergent validity, internal consistency, and variance inflation factor AVE = average variance extracted; CR = composite reliability.

Construct	Item	Factor loading	(AVE)	(CR)	Cronbach's α
Economic wellbeing	EW1	0.853	0.691	0.947	0.936
	EW2	0.846			
	EW3	0.849			
	EW4	0.865			
	EW5	0.829			
	EW6	0.708			
	EW7	0.841			
	EW8	0.850			
Economic sensitivity	ES1	0.837	0.576	0.915	0.895
	ES2	0.811			
	ES3	0.820			
	ES4	0.795			
	ES5	0.531			
	ES7	0.713			
	ES8	0.764			
	ES9	0.756			
Political sensitivity	PS1	0.834	0.555	0.896	0.869
	PS2	0.859			
	PS3	0.827			
	PS4	0.674			
	PS5	0.680			
	PS6	0.650			
	PS7	0.655			
Cultural sensitivity	CS1	0.892	0.775	0.96	0.951
	CS2	0.901			
	CS3	0.898			
	CS4	0.892			
	CS5	0.899			
	CS6	0.918			
	CS7	0.753			
Institutional sensitivity	IS1	0.778	0.718	0.947	0.935
	IS2	0.853			
	IS3	0.835			
	IS4	0.829			
	IS5	0.885			
	IS6	0.883			
	IS7	0.862			
Adaptive capacity	AC2	0.462	0.409	0.936	0.928
	AC3	0.781			
	AC4	0.693			
	AC5	0.525			
	AC6	0.658			
	AC7	0.785			
	AC8	0.773			
	AC9	0.550			
	AC10	0.488			

Table 2 (continued)

Construct	Item	Factor loading	(AVE)	(CR)	Cronbach's α
	AC11	0.619			
	AC12	0.491			
	AC19	0.678			
	AC20	0.475			
	AC21	0.827			
	AC22	0.634			
	AC23	0.728			
	AC24	0.547			
	AC27	0.673			
	AC30	0.571			
	AC32	0.723			
	AC34	0.479			
	AC35	0.682			
Technology adoption	TA1	0.769	0.567	0.962	0.958
	TA2	0.808			
	TA3	0.815			
	TA4	0.860			
	TA5	0.771			
	TA6	0.783			
	TA7	0.743			
	TA8	0.764			
	TA9	0.465			
	TA10	0.491			
	TA11	0.526			
	TA12	0.798			
	TA13	0.649			
	TA14	0.818			
	TA15	0.828			
	TA16	0.833			
	TA17	0.783			
	TA18	0.788			
	TA19	0.781			
	TA20	0.813			

Table 2 shows the results of the measurement model where all constructs have factor loadings greater than .4. This occurs after removing extremely low factor loading values below .4, particularly for economic sensitivity (ES6) and adaptive capacity (AC1, AC13, AC14, AC15, AC16, AC17, AC18, AC25, AC26, AC28, AC29, AC31, AC33, and AC36). As a result, in Table 2, all constructs have AVE scores greater than 0.5, the threshold value suggested by Hair et al. (2022), with the exception of adaptive capacity (AVE = 0.41). This occurs because many of its items have factor loading values less than 0.71. However, Fornell and Larcker (1981) stated that an AVE score of less than 0.5 is acceptable if the composite reliability (CR) value exceeds 0.6. Many other studies have used this principle, including Lam's (2012) study, which encountered the same problem. According to Table 2, the CR value for adaptive capacity is 0.94, which is significantly higher than 0.6, indicating that the construct's convergent validity remains acceptable. Table 2 shows that CR values for other constructs all are significantly higher than the minimum threshold of 0.6.

The constructs' internal consistency reliability is high for all constructs. As shown in Table 2, the Cronbach's alpha values for all constructs range from 0.87 to 0.96, all of which are significantly higher than 0.6, the minimum acceptable value according to Hair et al. (2022). Overall, the data on factor loading, AVE, CR, and Cronbach's alpha show convergent validity and reliability for all constructs used in this study.

6.2.2 Discriminant validity

The HTMT criterion is used to assess discriminant validity in this study. Henseler et al. (2015) found that the HTMT criterion outperforms both the Fornell and Larcker criterion and the assessment of (partial) cross-loadings when determining discriminant validity. According to Hair et al. (2022) and Ringle et al. (2024), all HTMT values must be less than 0.90 to meet the requirement. As shown in Table 3, the HTMT ratios for constructs (excluding control variables) range from 0.05 to 0.66, all of which are less than 0.9, indicating discriminant validity between two reflectively measured constructs. These findings can also help address potential concerns about acquiescent response bias, which refers to the tendency of respondents to agree with items regardless of their content. Since the survey did not include reverse-scored items, this could be seen as a possible limitation. However, the acceptable HTMT values suggest that the results are not primarily driven by uniform agreement across items.

Table 3: HTMT discriminant validity result with the inclusion of control variables in the analysis.

No.	Variable	1	2	3	4	5	6	7	8	9	10	11
1	Adaptive capacity											
2	Age	0.217										
3	Climate severity	0.295	0.097									
4	Cultural sensitivity	0.447	0.073	0.264								
5	Economic sensitivity	0.342	0.046	0.096	0.129							
6	Economic wellbeing	0.647	0.044	0.333	0.192	0.121						
7	Female	0.09	0.079	0.015	0.106	0.055	0.037					
8	Health adversity	0.199	0.110	0.071	0.075	0.111	0.082	0.009				
9	Income	0.288	0.195	0.020	0.138	0.092	0.253	0.182	0.001			
10	Institutional sensitivity	0.298	0.098	0.176	0.052	0.225	0.148	0.032	0.019	0.027		
11	Political sensitivity	0.430	0.085	0.107	0.294	0.365	0.124	0.035	0.242	0.124	0.290	
12	Technology adoption	0.656	0.252	0.213	0.379	0.228	0.506	0.134	0.131	0.194	0.145	0.175

6.3 Results for the structural model

This section presents the structural model results after verifying the measurement model results. Following Hair et al.'s (2022) recommendation, the multicollinearity issue was investigated before determining the significance and relevance of relationships. Table 4 displays the variance inflation factor (VIF) values for each independent variable and its corresponding dependent variable. The VIF values range from 1.054 to 2.205, indicating that no significant multicollinearity issues exist.

Table 4: Collinearity assessment of independent variables as predictors of adaptive capacity, economic well-being, and technology adoption.

	Variance Inflation Factor (VIF)		
Variable	Adaptive capacity	Technology adoption	Economic wellbeing
Female	1.056	1.056	1.076
Age	1.082	1.082	1.116
Income	1.112	1.112	1.257
Climate severity	1.123	1.123	1.232
Health adversity	1.054	1.054	1.128
Economic sensitivity	1.136	1.136	1.223
Political sensitivity	1.252	1.252	1.298
Cultural sensitivity	1.173	1.173	1.334
Institutional sensitivity	1.174	1.174	1.215
Adaptive capacity	NA	NA	2.205
Technology adoption	NA	NA	1.886

The results of the structural model are represented graphically in Figure 3. The R-square values are shown in the dependent variables' ovals, while beta coefficients and p-values (in parenthesis) for each independent variable are displayed next to their corresponding effect arrows.

Table 5 summarises the structural model's findings, including R^2 values for each dependent variable and path coefficients for the direct effects of all variables mentioned in the path model. As a result, economic well-being has the highest R^2 value (.537), followed by adaptive capacity (.391) and technology adoption (.288). R^2 values of 0.75, 0.50, and 0.25 are considered significant, moderate, and weak, respectively, in various social science disciplines (Hair et al., 2011). However, acceptable R^2 values differ depending on the research setting, and in some cases, an R^2 value as low as 0.10 is considered acceptable, particularly for previously unpublished research or when new independent variables are used, as in this study. Raithel et al. (2012), for example, claimed that R^2 values as low as 0.10 are sufficient, especially when predicting stock returns.

Beyond explanatory power (R^2), the model's predictive relevance was assessed using both the blindfolding and PLSpredict procedures. The blindfolding results indicated that all endogenous constructs had Q^2 values greater than zero: Adaptive Capacity ($Q^2 = 0.343$), Technology Adoption ($Q^2 = 0.241$), and Economic Wellbeing ($Q^2 = 0.180$), confirming medium to strong predictive relevance. The PLSpredict analysis further revealed moderate prediction errors, with RMSE values ranging from 0.813 to 0.911 and MAE values between 0.651 and 0.731, suggesting acceptable predictive accuracy for key constructs. However, the CVPAT comparison between the PLS-SEM and linear model (LM) benchmarks showed minimal average loss differences (0.007–0.020) and non-significant t-tests ($p > .46$), indicating that the predictive performance of the PLS-SEM model was statistically comparable to that of the LM benchmark. Finally, the SRMR values were 0.083 for the saturated model and 0.111 for the estimated model. The saturated model falls at the recommended threshold of 0.08 (Hu & Bentler, 1999), indicating an acceptable fit of the measurement model, while the higher estimated model SRMR reflects minor model complexity. Overall, the combination of strong explanatory power (R^2), adequate predictive relevance (Q^2), and acceptable model fit (SRMR) supports the robustness and quality of the proposed PLS-SEM model (Hair et al., 2022; Hu & Bentler, 1999).

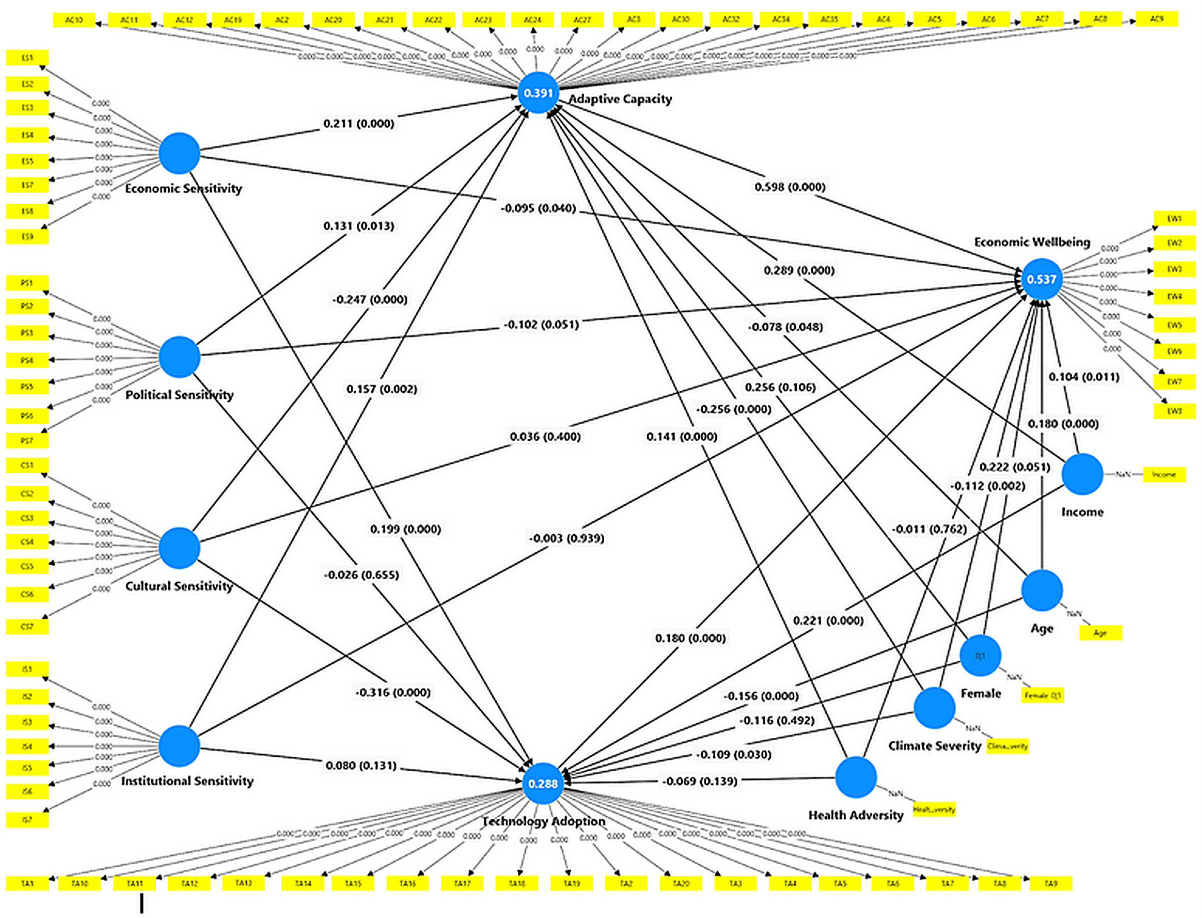

Figure 3: The finalized graphical output of path analysis for the interrelationships between all variables influencing the economic well-being of farmers in the Muda River Basin as a result of climate change sensitivities caused by climate extremes. Note: The constructs contain R-squares; p values are shown for the outer model, whilst standardised path coefficients (with p-values in brackets) are shown for the inner model. Items with low factor loadings were already removed from the analysis.

Table 5: Direct effects for all variables specified in the path model

Dependent variable	Direct effect	β coefficient	Standard deviation (STDEV)	t statistic (|O/STDEV|)	p value	R^2	Q^2 (Stone–Geisser)
Economic wellbeing	Adaptive capacity → Economic wellbeing	0.598	0.053	11.356	0.000	0.537	0.180
	Technology adoption → Economic wellbeing	0.180	0.052	3.498	0.000		
	Economic sensitivity → Economic wellbeing	-0.095	0.046	2.081	0.037		
	Political sensitivity → Economic wellbeing	-0.102	0.053	1.945	0.052		
	Cultural sensitivity → Economic wellbeing	0.036	0.043	0.844	0.398		
	Institutional sensitivity → Economic wellbeing	-0.003	0.044	0.077	0.939		
	Income → Economic wellbeing	0.104	0.041	2.557	0.011		

Table 5 (continued)

Dependent variable	Direct effect	β coefficient	Standard deviation (STDEV)	t statistic (|O/STDEV|)	p value	R^2	Q^2 (Stone–Geisser)
	Female → Economic wellbeing	0.222	0.114	1.947	0.052		
	Age → Economic wellbeing	0.180	0.037	4.901	0.000		
	Climate severity → Economic wellbeing	-0.112	0.035	3.171	0.002		
	Health adversity → Economic wellbeing	-0.011	0.036	0.300	0.765		
Adaptive capacity	Economic sensitivity → Adaptive capacity	0.211	0.046	4.637	0.000	0.391	0.343
	Political sensitivity → Adaptive capacity	0.131	0.053	2.481	0.013		
	Cultural sensitivity → Adaptive capacity	-0.247	0.043	5.741	0.000		
	Institutional sensitivity → Adaptive capacity	0.157	0.052	3.026	0.002		
	Income → Adaptive capacity	0.289	0.048	6.009	0.000		
	Female → Adaptive capacity	0.256	0.160	1.599	0.110		
	Age → Adaptive capacity	-0.078	0.040	1.957	0.050		
	Climate severity → Adaptive capacity	-0.256	0.045	5.740	0.000		
	Health adversity → Adaptive capacity	0.141	0.039	3.605	0.000		
Technology adoption	Economic sensitivity → Technology adoption	0.199	0.048	4.125	0.000	0.288	0.241
	Political sensitivity → Technology adoption	-0.026	0.057	0.454	0.650		
	Cultural sensitivity → Technology adoption	-0.316	0.055	5.760	0.000		
	Institutional sensitivity → Technology adoption	0.080	0.052	1.541	0.123		
	Income → Technology adoption	0.221	0.045	4.913	0.000		
	Female → Technology adoption	-0.116	0.172	0.675	0.500		
	Age → Technology adoption	-0.156	0.041	3.794	0.000		
	Climate severity → Technology adoption	-0.109	0.050	2.178	0.029		
	Health adversity → Technology adoption	-0.069	0.048	1.458	0.145		

Note: The direction of arrows indicates the direction of effects. The path coefficients and t-statistics were calculated using bootstrapping with 10,000 replications.

Table 5 shows that both adaptive capacity ($\beta = .6$, $p < .01$) and technology adoption ($\beta = .18$, $p < .01$) have a positive and significant impact on economic wellbeing. This demonstrates that increased adaptive capacity and the use of technology will improve farmers' economic status. Nonetheless, the coefficient estimate of adaptable capacity was three times larger than that of technology adoption, highlighting the critical role of adaptive capacity in the economic well-being of MRB farmers. This study examined the effects of four different types of social sensitivity. Only economic sensitivity (β = -.10; $p < .05$) had a negative impact on the economic well-being of farmers after controlling for other factors. The direct effects of cultural, political, and institutional sensitivity were all non-significant, with p-values of more than 5%. The negative relationship between economic sensitivity and economic wellbeing is understandable, as farmers affected by climate change felt deprived of their economic well-being.

Furthermore, the effects of the control factors on the economic status were assessed. Economic well-being is positively influenced by age (β = .18, $p < .01$) and income (β = .10, $p < .05$), but negatively by climate severity (β = -.11, $p < .01$). At the 10% level, health adversity had no effect on economic wellbeing, as shown in Table 5. These findings revealed that the elderly and high-income earners had better economic well-being, whereas farmers who believed climate change had worsened had poorer economic well-being.

In this study, it is critical to determine whether farmers' sensitivity to climate change has led them to embrace technology and improve on adaptation in their work. Table 5 shows that economic sensitivity (β = .21; $p < .01$), institutional sensitivity (β = .16; $p < .01$), and political sensitivity (β = .13; $p < .05$) all have a positive and significant impact on adaptive capacity. Based on these findings, it is possible to conclude that farmers' adaptation levels increase when they believe climate change is affecting their economic activities. Furthermore, the findings on institutional and political sensitivity show that if institutions and political representatives are perceived to be more sensitive to climate change, farmers are more likely to adapt to it. Cultural sensitivity had a significant negative impact on adaptive capacity (β = -.25; $p < .01$), outweighing the effects of economic, institutional, and political sensitivity. This means that farmers who have been affected by extreme weather conditions, as well as the loss of physical socialisation and cultures, have become less adapted to the effects of climate change in their lives. This finding is significant because social capital in the form of strong networks and community relations helps to increase resource availability while also improving community resilience and adaptation to the effects of climate change (Pelling & High, 2005; Tompkins & Adger, 2004). As a result, it could be argued that the overall degradation of this function in the community is due to extreme weather, which has limited face-to-face information sharing and hampered farmers' learning processes, both of which are necessary for the enhancement of their adaptive capacity.

Certain control factors have a significant influence on adaptive capacity. Income has a strong positive relationship with adaptation (β = .29; $p < .01$), indicating that high-income earners are better able to adjust their life and work during climate change events. Finally, the researcher was unable to establish a significant relationship between gender and farmers' adaptive capacity in this study. However, age has a negative impact on adaptive capacity (β = -.08; $p < .05$), suggesting that young farmers adapt more easily than older ones. Surprisingly, analyses revealed that perceived climate severity was negatively associated with adaptive capacity (β = -.26, $p < .01$), whereas health adversity had a positive effect (β = .14, $p < .01$). This suggests that farmers who believe their health has been affected by climatic extremes will try to strengthen their resilience and adaptability to the changes.

Those who perceive climate change as more severe tend to report lower adaptive capacity. This suggests that farmers who view extreme climatic events as highly threatening may experience heightened psychological stress, which can undermine their resilience. While the current study did not directly measure climate anxiety as a latent construct, perceived severity may capture elements of climate-related anxiety, reflecting farmers' worry about the impacts of climate change. Unlike in Western contexts, where "climate anxiety" is often discussed in terms of media exposure and general environmental concern, in the case of Malaysian farmers, these perceptions may be more accurately understood as immediate reactions to direct experiences with extreme climate events.

Stress, sadness, and helplessness can indicate mental health deterioration related to climate change. Mental disorders can impair an individual's cognitive function, limiting their ability to understand climate variation and change. The fear of the unknown and the future that climate change brings leads to a lack of innovation or to risk aversion. This study suggests that limited access to balanced information, along with limited critical thinking ability, especially in populations with limited recent formal education, may contribute to confusion, anxiety, and irrational responses to climate change. Providing accurate and accessible information is crucial, but additional efforts may be needed to support cognitive engagement and adaptive decision-making across all segments of the farming population. Such an attitude may cause a community to ignore new technologies or approaches that would otherwise improve their flexibility, adaptive capacity, and thus productivity.

The term 'climate anxiety' refers to a condition in which people find it difficult to get up and do something to combat the negative effects of climate change. Climate anxiety may also cause self-centredness, leading to a decrease in community engagement in addressing climate change issues. Similarly, these factors can deteriorate relations and undermine the potential for community-based adaptation (Albrecht, 2011; Berry et al., 2010; Clayton et al., 2017; Cunsolo & Ellis, 2018; Hickman, 2020; Hickman et al., 2021).

Furthermore, the influence of sensitivity on technology adoption was investigated. According to Table 5, the study's findings indicate that political and institutional sensitivities had no influence on technology adoption. Farmers with higher economic sensitivity to extreme weather conditions are more likely to adopt technology in agriculture to increase production ($\beta = .20$; $p < .01$). This study found that cultural sensitivity has a negative impact on technology adoption ($\beta = -.32$; $p < .01$), similar to its negative impact on adaptive capacity ($\beta = -.25$; $p < .01$). However, the former has a larger effect size ($\beta = -.32$) than the latter ($\beta = -.25$). Based on these findings, it is possible to conclude that sociocultural activities are important in MRB communities, particularly for farmers who need to learn new agricultural practices in light of climate change and modern farming methods. Social interactions, such as social activities or cultural engagements, may have been the channels through which farmers obtained information and knowledge that protected them from the effects of climate events on their economic well-being.

The effects of the control variables on technology adoption were also investigated. Income was found to have a positive influence on technology adoption ($\beta = .22$; $p < .01$). As a result, farmers with higher incomes are more likely and capable of assessing technology and incorporating it into their economic activities. In Table 5, the gender of farmers and perceived health adversity did not significantly affect technology adoption. Although the relationship between age and adaptive capacity was not statistically significant at the 5% level of significance, this study found that older farmers are less likely to adopt technology than younger farmers ($\beta = -.16$; $p < .01$). This demonstrates that younger farmers are more capable of understanding and adopting new technologies to improve their economic activities. This could also be explained by a generational cognitive difference, where younger cohorts in this part of Malaysia are more familiar with technology use and digital tools, allowing them to integrate innovation more effectively into their farming practices.

Additionally, climatic severity had a significant negative impact ($\beta = -.11$; $p < .05$) on technology adoption. This finding is consistent with the concept of 'climate anxiety', which states that farmers who believe climate change is worse are less likely to choose the best strategy for dealing with climate extremes. This finding is consistent with the study's findings about the negative direct effects of 'climate anxiety' on adaptive capacity and economic well-being. Farmers who have experienced more serious 'climate anxiety' are more pessimistic about their economic well-being, and they are also less capable of dealing with climate change because they have adopted less technology and achieved less adaptive capacity. Although climate anxiety was not found to have a statistically significant direct effect on technology adoption, it is possible that this is due to indirect pathways through other variables. One plausible explanation is that brighter and better-informed farmers may be less likely to perceive climate change as an overwhelming or insurmountable threat. These farmers are also more open to understanding and adopting new technologies that help them manage risks and improve productivity.

In light of this, one of the most pressing questions raised in this study, as previously stated, is whether adaptive capacity and technology adoption can help to mediate the effects of sensitivity on economic well-being. According to Table 5, only economic sensitivity had a direct impact on economic wellbeing, with the effect being negative and significant at the 5% level. This suggests that farmers who report higher economic sensitivity to climate change, meaning they perceive greater economic risks and disruptions due to climate variability, also tend to report lower economic well-being. This interpretation aligns with the hypothesised direction of influence, where perceived vulnerability leads to economic strain, rather than the other way around. Nonetheless, this relationship should be interpreted with caution, as subjective perceptions can reflect both actual exposure and subjective evaluation. In contrast, political, institutional, and cultural sensitivities were found to have no significant direct impact on economic well-being. Table 6 shows the indirect effect analysis, in which adaptive capacity and technology adoption mediated the effects of climate change sensitivities on economic wellbeing.

Table 6: Specific indirect effects for all variables specified in the path model.

Mediator	Specific indirect effect	β coefficient	Standard deviation (STDEV)	t statistic ($\|O/ST$
Adaptive capacity	Economic sensitivity → Adaptive capacity → Economic wellbeing	0.126	0.030	4.148
	Political sensitivity → Adaptive capacity → Economic wellbeing	0.078	0.032	2.460
	Cultural sensitivity → Adaptive capacity → Economic wellbeing	-0.148	0.030	4.968
	Institutional sensitivity → Adaptive capacity → Economic wellbeing	0.094	0.033	2.820
	Income → Adaptive capacity → Economic wellbeing	0.173	0.030	5.708
	Female → Adaptive capacity → Economic wellbeing	0.153	0.098	1.568
	Age → Adaptive capacity → Economic wellbeing	-0.046	0.025	1.872
	Climate severity → Adaptive capacity → Economic wellbeing	-0.153	0.029	5.251
	Health adversity → Adaptive capacity → Economic wellbeing	0.085	0.025	3.438
Technology adoption	Economic sensitivity → Technology adoption → Economic wellbeing	0.036	0.014	2.608
	Political sensitivity → Technology adoption → Economic wellbeing	-0.005	0.011	0.439
	Cultural sensitivity → Technology adoption → Economic wellbeing	-0.057	0.019	2.971
	Institutional sensitivity → Technology adoption → Economic wellbeing	0.014	0.011	1.353
	Income → Technology adoption → Economic wellbeing	0.040	0.015	2.649
	Female → Technology adoption → Economic wellbeing	-0.021	0.033	0.636
	Age → Technology adoption → Economic wellbeing	-0.028	0.011	2.573
	Climate severity → Technology adoption → Economic wellbeing	-0.020	0.011	1.808
	Health adversity → Technology adoption → Economic wellbeing	-0.012	0.009	1.344

Note: The direction of arrows indicates the direction of effects. The path coefficients and t-statistics were calculated using bootstrapping with 10,000 replications.

Table 6 shows that adaptive capacity significantly mediates the impact of cultural sensitivity ($\beta =$ -.15; $p <$ .01), economic sensitivity ($\beta =$ .13; $p <$ .01), institutional sensitivity ($\beta =$ .09; $p <$ 0.01), and political sensitivity ($\beta =$ .08; $p <$ .05) on economic well-being. The indirect effect of cultural sensitivity was the most significant, and it was negative. Adaptive capacity mediated the effects of control factors, with income ($\beta =$ .17; $p <$ .01), climate severity ($\beta =$ -.15; $p <$ .01), and health adversity ($\beta =$ .09; $p <$ .01) having the largest and smallest indirect significant effect sizes on economic well-being, respectively. Adaptive capacity did not play a significant role in mediating the impact of age and gender on economic well-being.

Furthermore, Table 6 shows that cultural (β = -.06; $p < .01$) and economic (β = .04; $p < .01$) sensitivities have an indirect effect on economic well-being through technology adoption. Nonetheless, technology adoption did not channel the impacts of political and institutional sensitivities to economic well-being. Technology adoption mediated the effect of income on economic well-being (β = .04; $p < .01$). The impacts of age, gender, climate severity, and health adversity on economic well-being were not significantly mediated by technology adoption.

7 Discussion

Climate change is impacting agricultural communities in the MRB. This study focuses on farmers' perceptions of climate variability and extreme weather events, which they experience as disruptions to their agricultural livelihoods. While climate change is widely understood to increase the frequency and intensity of such events globally, this study does not provide meteorological data to demonstrate that such changes have occurred specifically in this part of Malaysia. Rather, it relies on farmers' reported experiences and perceived sensitivity to climate extremes to explore how these perceptions influence their adaptive capacity and technology adoption. The current study, which was inspired by rational choice theory (RCT), sought to investigate how climate change sensitivity, specifically economic, political, cultural, and institutional sensitivities, had a statistical impact on farmers' adaptive capacity to climate extremes and technology adoption in agricultural activities. This study also used path analysis to investigate how adaptive capacity and technology adoption mediate the relationships between climate change sensitivity and economic wellbeing. Overall, farmers in MRB farming communities perceived themselves to be more sensitive economically (3.48), followed by political (3.14), institutional (2.54), and cultural (2.01) sensitivity, all measured on a Likert scale from 1 to 5.

This study used Rational Choice Theory (RCT), which states that farmers must consider available options based on their knowledge and understanding of climate extremes. The farmers' ultimate goal is to achieve the best possible outcome in their agricultural activities. This includes high productivity and sustainability, which can be achieved through increased adaptive capacity and technology adoption, as hypothesised in the current study. Farmers are unlikely to change or improve unless confronted with external forces, such as climate extremes, because they must invest effort and pay a price to improve their adaptive capacity and adopt new technologies. As a result, it is critical to recognise that their own initiative or sense of thought in adjusting to climate extremes is determined by the trigger factor, which refers to the vulnerability or sensitivity they experienced during extreme climate events, specifically the economic, political, cultural, and institutional sensitivities outlined by Fenton et al. (2007) and Marshall et al. (2010). In this study, farmers' perceived trigger factors (i.e., sensitivities) are viewed as sources of awareness, information, or knowledge of uncertainties that may prompt them to develop strategies based on available options, such as whether or not to put more effort into becoming more adaptive or adopt technology for dealing with climate extremes, with the ultimate goal of achieving the best outcome in their agricultural or business activities.

In summary, this study found that both technology adoption and adaptive capacity directly improved farmers' economic wellbeing. Climate change sensitivity variables, such as economic, political, and institutional sensitivity, had a positive effect on adaptive capacity, while cultural sensitivity had a negative impact. Cultural and economic sensitivity had the greatest impact among these. Farmers who believe they have been economically impacted and that the political and institutional environments are effective in assisting the community in dealing with climate extremes are more likely to develop the ability to adapt to changes in their environment. Furthermore, the current study suggests that sociocultural activities have served as a means of knowledge dissemination among farmers, which is an important source of adaptation and technology adoption. As a result, it is worth noting that disengagement or disruption in sociocultural aspects has hampered farmers' ability to adapt to climate change. Furthermore, path analysis revealed that adaptive capacity played an important role in mitigating the impact of these four sensitivities on economic wellbeing.

Only economic and cultural sensitivity had significant positive and negative effects on technology adoption, respectively. This finding is consistent with previous findings that of the four sensitivities, cultural (-) and economic (+) sensitivity had the greatest effects on adaptive capacity. Furthermore, technology adoption mediated the impact of cultural and economic sensitivity on economic well-being. These findings are significant for this study because political and institutional sensitivities had a strong positive impact on adaptive capacity but not on technology adoption. As a result, one could argue that farmers' perceptions of government effectiveness (i.e., political and institutional features) are important for the development of adaptive capacity but did not lead to technology adoption among MRB farmers. Similarly, it is possible that agricultural technology is expensive to acquire, and as a result, when farmers perceive serious efforts from the institutional and political sides, they tend to develop their adaptive capacity rather than incorporating technology into their economic activity in order to achieve higher economic well-being in the long run. In this case, it is worth noting that political and institutional sensitivities are based on what farmers see of what others (politicians, institutions, or government) are doing, whereas economic and cultural sensitivities are based on what farmers have personally experienced or suffered (economically or culturally) as a result of climate change events. However, it should be noted that being more adaptive can take many forms, including the sixteen dimensions identified by Marshall et al. and used in this study. However, the current study did not go into detail about each dimension and its relationship to sensitivity.

Given that adaptive capacity has a threefold greater positive effect than technology adoption on economic well-being, it is worthwhile to emphasise the development of adaptive capacity among farmers in order to ensure the sustainability of agricultural communities. The development of adaptive capacity is consistent with the farming community's empowerment concept, which is motivated by political, institutional, cultural, and economic sensitivity to climate change. To empower the area's farming communities and protect them from current and future climate change vulnerabilities, it is critical to support long-term approaches to adaptation and coping mechanisms. To address these challenges, governments, research institutions, and other stakeholders must work together across sectors to define a future of sustainable wellbeing for MRB farmers. At the same time, the findings should be interpreted in light of certain limitations, which point to avenues for future research.

8 Limitations and Future Research

This study is based on cross-sectional, self-reported data drawn from a homogeneous convenience sample of MRB farmers, predominantly male. Consequently, the findings should be interpreted as associative rather than causal. Measurement limitations include the use of single-item indicators for perceived climate severity and health adversity, as well as a technology adoption construct reflecting perceived innovation attributes rather than observed behaviors. Although diagnostic tests indicated acceptable levels of common method variance, the potential for residual bias cannot be ruled out.

Future research should employ longitudinal (panel or cohort) designs to better capture temporal dynamics and causal relationships. Incorporating objective exposure metrics, such as meteorological or flood records, would enhance validity. Using validated scales to assess climate-related anxiety is also recommended. Moreover, examining actual behavioral adoption and capital constraints (for example, credit access, subsidy participation, and farm size) would offer deeper insights into adaptation processes. Finally, testing moderated mediation pathways (such as income, age, and extension contact) could clarify the conditions under which sensitivity influences adaptation and well-being outcomes.

Competing interests: The authors declare no competing interests.

Ethical approval: This project received ethical approval from the Universiti Putra Malaysia's Ethics Committee for Research Involving Human Subjects. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Funding declaration: This study was supported by the Ministry of Higher Education Malaysia under the Long-Term Research Grant Scheme (LRGS). Funding was provided specifically for sub-project number 4 (Reference: LRGS/1/2020/UKM/01/6/4), which is part of the principal LRGS program (Reference: LRGS/1/2020/UKM/01/6).

Informed consent: Informed consent was obtained from all participants prior to their participation.

Bibliography

Abd Halim, M., Saudi, A. S. M., Kamarudin, M. K. A., Mahmud, M., Krishnan, A. B., & Isa, K. N. M. (2018). Assessment on regional flood risk trend in northern region of Malaysia: Case study in Muda River Basin, Kedah. *International Journal of Engineering & Technology, 7*(4.34), 75-80.

Adade Williams, P., Sikutshwa, L., & Shackleton, S. (2020). Acknowledging indigenous and local knowledge to facilitate collaboration in landscape approaches: Lessons from a systematic review. *Land, 9*(9), 331.

Adger, W. N. (2000). Social and ecological resilience: Are they related? *Progress in Human Geography, 24*(3), 347-364.

Adger, W. N. (2006). Vulnerability. *Global Environmental Change, 16*(3), 268-281.

Adger, W. N., Arnell, N. W., & Tompkins, E. L. (2005a). Successful adaptation to climate change across scales. *Global Environmental Change, 15*(2), 77-86.

Adger, W. N., Brooks, N., Bentham, G., Agnew, M., & Eriksen, S. (2005b). *New indicators of vulnerability and adaptive capacity. Technical Report 7,* Tyndall Centre for Climate Change Research, Norwich, UK.

Adger, W. N., Barnett, J., Brown, K., Marshall, N., & O'Brien, K. (2013a). Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change, 3*(2), 112-117.

Adger, W.N., Quinn, T., Lorenzoni, I., Murphy, C., & Sweeney, J. (2013b). Changing social contracts in climate-change adaptation. *Nature Climate Change, 3*(4), 330-333.

Afroz, R., Akhtar, R., & Farhana, P. (2017). Willingness to pay for crop insurance to adapt flood risk by Malaysian farmers: An empirical investigation of Kedah. *International Journal of Economics and Financial Issues, 7*(4), 1-9.

Agrawal, A. (2010). Local institutions and adaptation to climate change. In R. Mearns & A. Norton (Eds.), *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World*. World Bank.

Aisen, A., & Veiga, F. J. (2013). How does political instability affect economic growth? *European Journal of Political Economy, 29,* 151-167.

Akhtar, R., Masud, M. M., & Afroz, R. (2019). Perception of climate change and the adaptation strategies and capacities of the rice farmers in Kedah, Malaysia. *Environment and Urbanization ASIA, 10*(1), 99-115.

Alam, M. M., Siwar, C., & Al-Amin, A. Q. (2010a). Climate change adaptation policy guidelines for agricultural sector in Malaysia. *Asian Journal of Environmental and Disaster Management, 2*(4), 463-469.

Alam, M. M., Talib, B., Siwar, C., & Toriman, M. E. (2010b). The impacts of climate change on paddy production in Malaysia: Case of paddy farming in North West Selangor. Proceedings of the International Conference of the 4th International Malaysia-Thailand Conference on South Asian Studies. National University of Malaysia, Mar 25-26.

Alam, M. M., Siwar, C., Talib, B., Mokhtar, M., & Toriman, M. (2012). Climate change adaptation policy in Malaysia: Issues for agricultural sector. *African Journal of Agricultural Research, 7*(9), 1368-1373.

Albrecht, G. A. (2011). Chronic environmental change: Emerging "psychoterratic" syndromes. In I. Weissbecker (Ed.), *Climate Change and Human Well-Being: Global Challenges and Opportunities* (pp. 43–56). New York, NY: Springer.

Atkinson, N. L. (2007). Developing a questionnaire to measure perceived attributes of eHealth innovations. *American Journal of Health Behavior, 31*(6), 612-621.

Azevedo, P., Gomes, J., & Romão, M. (2023). Supply chain traceability using blockchain. *Operations Management Research, 16*(3), 1359-1381.

Barnett, J., & Adger, W. N. (2007). Climate change, human security and violent conflict. *Political Geography, 26*(6), 639-655.

Berkes, F., Colding, J., & Folke, C. (2000). Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications, 10*(5), 1251-1262.

Berry, H. L., Bowen, K., & Kjellstrom, T. (2010). Climate change and mental health: A causal pathways framework. *International Journal of Public Health, 55,* 123-132.

Bertin, S., Ohana, S., & Strauss-Kahn, V. (2016). Revisiting the link between political and financial crises in Africa. *Journal of African Economies, 25*(3), 323-366.

Biermann, F., Pattberg, P., van Asselt, H., & Zelli, F. (2009). The fragmentation of global governance architectures: A framework for analysis. *Global Environmental Politics, 9*(4), 14-40.

Brooks, N., Adger, W. N., & Kelly, P. M. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change, 15*(2), 151-163.

Brou, D., & Zeigler-Hill, V. (Eds.). (2020). *Economics and Well-Being*. Springer.

Buhaug, H. (2010). Climate not to blame for African civil wars. *Proceedings of the National Academy of Sciences USA, 107*(38), 16477-16482.

Bulkeley, H., & Betsill, M. M. (2013). *Cities and Climate Change*. Routledge.

Cafer, A. M., & Rikoon, J. S. (2018). Adoption of new technologies by smallholder farmers: The contributions of extension, research institutes, cooperatives, and access to cash for improving tef production in Ethiopia. *Agriculture and Human Values, 35,* 685-699.

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2018). A meta-analysis of the effects of climate change on crop yields. *Nature Climate Change, 8*(4), 271-281.

Chan, N. W. (2014). Impacts of disasters and disaster risk management in Malaysia: The case of floods. In D. P. Aldrich, S. Oum, & Y. Sawada (Eds.), *Resilience and Recovery in Asian Disasters: Community Ties, Market Mechanisms, and Governance* (pp. 239-265). Tokyo, Japan: Springer.

Cinner, J. E., Daw, T., & McClanahan, T. R. (2009). Socioeconomic factors that affect artisanal fishers' readiness to exit a declining fishery. *Conservation Biology, 25*(2), 349-356.

Clayton, S., Manning, C., Krygsman, K., & Speiser, M. (2017). *Mental Health and Our Changing Climate: Impacts, Implications, and Guidance*. Washington DC: American Psychological Association and ecoAmerica.

Crate, S. A., & Nuttall, M. (2016). *Anthropology and Climate Change: From Encounters to Actions.* Routledge.

Crentsil, C., Gschwandtner, A., & Wahhaj, Z. (2020). The effects of risk and ambiguity aversion on technology adoption: Evidence from aquaculture in Ghana. *Journal of Economic Behavior & Organization, 179,* 46-68.

Cruikshank, J. (2001). Glaciers and climate change: Perspectives from oral tradition. *Arctic, 54*(4), 377-393.

Cunsolo, A., & Ellis, N. R. (2018). Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change, 8*(4), 275-281.

Daud, N., & Safiei, R. H. (2018). *Kajian Sosio-ekonomi Perikanan Darat di Lembangan Sungai Muda*. [Socio-economic research on inland fisheries in Muda River basin]. Fisheries Research Institute.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly, 13*(3), 319-340.

Davis, K., Nkonya, E., Kato, E., Mekonnen, D. A., Odendo, M., Miiro, R., & Nkuba, J. (2012). Impact of farmer field schools on agricultural productivity and poverty in East Africa. *World Development, 40*(2), 402-413.

Denashurya, N. I., Nurliza, Dolorosa, E., Kurniati, D., & Suswati, D. (2023). Overcoming barriers to ISPO certification: Analyzing the drivers of sustainable agricultural adoption among farmers. *Sustainability, 15*(23), 16507.

Deressa, T. T., Hassan, R. M., Ringler, C., Alemu, T., & Yesuf, M. (2009). Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global Environmental Change, 19*(2), 248-255.

Dutta, M. J. (2007). Communicating about culture and health: Theorizing culture-centered and cultural sensitivity approaches. *Communication Theory, 17*(3), 304-328.

Eakin, H., & Lemos, M. C. (2006). Adaptation and the state: Latin America and the challenge of capacity-building under globalization. *Global Environmental Change, 16*(1), 7-18.

Emani, S., Peters, E., Desai, S., Karson, A. S., Lipsitz, S. R., LaRocca, R., & Bates, D. W. (2018). Perceptions of adopters versus non-adopters of a patient portal: An application of diffusion of innovation theory. *BMJ Health & Care Informatics, 25*(3), 149-157.

Engle, N. L. (2011). Adaptive capacity and its assessment. *Global Environmental Change, 21*(2), 647-656.

Ercan, A., Fauzi, M., & Kavvas, M. L. (2013). The impact of climate change on sea level rise at Peninsular Malaysia and Sabah-Sarawak. *Hydrological Processes, 27*(3), 367-377.

Fan, S., Luo, X., & Han, P. (2023). Conflict resolution between multi-level government and farmers in land expropriation based on Institutional Credibility Theory: Empirical evidence from Shandong Province, China. *Land, 12*(4), 844.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39,* 175-191.

Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic Development and Cultural Change, 33*(2), 255-298.

Fenton, M., Kelly, G., Vella, K., & Innes, J. (2007). Climate change and Great Barrier Reef: Industries and communities. In J. E. Johnson & P. A. Marshall (Eds.), *Climate Change and the Great Barrier Reef. A Vulnerability Assessment* (pp. 745-771). Townsville, Australia: GBRMPA and Australian Greenhouse Office.

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources, 30*, 441-473.

Ford, J. D., Smit, B., & Wandel, J. (2006). Vulnerability to climate change in the Arctic: A case study from Arctic Bay, Canada. *Global Environmental Change, 16*(2), 145-160.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of Marketing Research, 18*(1), 39-50.

Frimpong, F., Asante, M. D., Peprah, C. O., Amankwaa-Yeboah, P., Danquah, E. O., Ribeiro, P. F., & Botey, H. M. (2023). Water-smart farming: Review of strategies, technologies, and practices for sustainable agricultural water management in a changing climate in West Africa. *Frontiers in Sustainable Food Systems, 7,* 1110179.

Gemenne, F., Barnett, J., Adger, W. N., & Dabelko, G. D. (2014). Climate and security: evidence, emerging risks, and a new agenda. *Climatic Change, 123*(1), 1-9.

Geng, W., Liu, L., Zhao, J., Kang, X., & Wang, W. (2024). Digital technologies adoption and economic benefits in agriculture: A mixed-methods approach. *Sustainability, 16*(11), 4431.

Ghani, A. A., Ali, R., Zakaria, N. A., Hasan, Z. A., Chang, C. K., & Ahamad, M. S. S. (2010). A temporal change study of the Muda River system over 22 years. *International Journal River Basin Management, 8*(1), 25-37.

Graham, C. (2011). *The Pursuit of Happiness: An Economy of Well-Being*. Brookings Institution Press.

Grothmann, T., & Patt, A. (2005). Adaptive capacity and human cognition: The process of individual adaptation to climate change. *Global Environmental Change, 15*(3), 199-213.

Gupta, J., Termeer, C., Klostermann, J., Meijerink, S., van den Brink, M., Jong, P., & Bergsma, E. (2010). The adaptive capacity wheel: A method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science & Policy, 13*(6), 459-471.

Hair, J. F., Ringle, C. M., & Sarstedt, M. (2011). PLS-SEM: Indeed a silver bullet. *Journal of Marketing Theory and Practice, 19*(2), 139-151.

Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). When to use and how to report the results of PLS-SEM. *European Business Review, 31*(1), 2-24.

Hair, J. F., Hult, G. T. M., Ringle, C. M., & Sarstedt, M. (2022). *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)*. Thousand Oaks CA: SAGE Publications.

Harvey, C. A., Saborio-Rodríguez, M., Martinez-Rodríguez, M. R., Viguera, B., Chain-Guadarrama, A., Vignola, R., & Alpizar, F. (2018). Climate change impacts and adaptation among smallholder farmers in Central America. *Agriculture & Food Security, 7*(1), 1-20.

Hays, R., & Revicki, D. A. (2005). Reliability and validity (including responsiveness). In P. Fayers & R. Hays (Eds.), *Assessing Quality of Life in Clinical Trials: Methods and Practice, 2nd ed.* (pp. 25-29). New York: Oxford Univ. Press.

Hebsale Mallappa, V. K., & Pathak, T. B. (2023). Climate smart agriculture technologies adoption among small-scale farmers: A case study from Gujarat, India. *Frontiers in Sustainable Food Systems, 7,* 1202485.

Henderson, R. M., Reinert, S. A., Dekhtyar, P., & Migdal, A. (2016). *Climate change in 2018: Implications for business*. Harvard Business School Background Note 317-032.

Henseler, J., Ringle, C. M., & Sarstedt, M. (2015). A new criterion for assessing discriminant validity in variance-based structural equation modeling. *Journal of the Academy of Marketing Science, 43,* 115-135.

Hickman, C. (2020). We need to (find a way to) talk about... eco-anxiety. *Journal of Social Work Practice, 34*(4), 411-424.

Hickman, C., Marks, E., Pihkala, P., Clayton, S., Lewandowski, R. E., Mayall, E. E., & van Susteren, L. (2021). Climate anxiety in children and young people and their beliefs about government responses to climate change: A global survey. *Lancet Planetary Health, 5*(12), e863-e873.

Hu, L. T., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal, 6*(1), 1-55.

Hyndman, D., & Hyndman, D. (2016). *Natural Hazards and Disasters*. Cengage Learning, Boston.

IPCC (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge Univ. Press.

IPCC (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge Univ. Press. https://www.ipcc.ch/report/ar6/wg1/

ISAAA (2017). *Global status of commercialized biotech/GM crops in 2017: Biotech crop adoption surges as economic benefits accumulate in 22 years*. ISAAA Brief No. 53. ISAAA: Ithaca, NY.

Jager, J., Putnick, D. L., & Bornstein, M. H. (2017). II. More than just convenient: The scientific merits of homogeneous convenience samples. *Monographs of the Society for Research in Child Development, 82*(2), 13-30.

Joo, S. (2008). Personal financial wellness. In J. J. Xiao (Ed.), *Handbook of Consumer Finance Research* (pp. 21-33). New York: Springer.

Julien, P. Y., Ab. Ghani, A., Zakaria, N. A., Abdullah, R., Chang, C. K., Ramli, R., & Dinor, J. (2006). *Design option of the flood mitigation plan of Sg. Muda, Sungai Muda, Kedah*. Research Report No. JPS(PP)/TB/2/06. Kuala Lumpur, Malaysia: Department of Irrigation and Drainage, 149.

Khatun, M., Sarkar, S., Era, F. M., Islam, A. K. M., Anwar, M. D. P., Fahad, S., et al. (2021). Drought stress in grain legumes: Effects, tolerance mechanisms and management. *Agronomy, 11,* 2374.

Lam, L. W. (2012). Impact of competitiveness on salespeople's commitment and performance. *Journal of Business Research, 65*(9), 1328-1334.

Lee, K. Y., Amir, S. R. M. S., & Khaironizam, M. Z. (2013). *Assessment of freshwater fisheries in Ulu Muda, Kedah, Malaysia*. WWF Malaysia.

Lemma D, H., Mengistu, A., Kuma, T., & Kuma, B. (2018). Improving milk safety at farm-level in an intensive dairy production system: relevance to smallholder dairy producers. *Food Quality and Safety, 2*(3), 135-143.

Li, J., Ma, W., & Zhu, H. (2024). A systematic literature review of factors influencing the adoption of climate-smart agricultural practices. *Mitigation and Adaptation Strategies for Global Change, 29*(1), 1-38.

Luhaim, Z. B., Tan, M. L., Tangang, F., Zulkafli, Z., Chun, K. P., Yusop, Z., & Yaseen, Z. M. (2021). Drought variability and characteristics in the Muda River Basin of Malaysia from 1985 to 2019. *Atmosphere,* *12*(9), 1210.

Makate, C. (2020). Local institutions and indigenous knowledge in adoption and scaling of climate-smart agricultural innovations among sub-Saharan smallholder farmers. *International Journal of Climate Change Strategies and Management, 12*(2), 270-287.

Malhotra, N. (2010). *Marketing Research: An Applied Orientation* (6th ed.). Prentice-Hall.

Marshall, N. A., Fenton, D. M., Marshall, P. A., & Sutton, S. G. (2007). How resource dependency can influence social resilience within a primary resource industry. *Rural Sociology, 72*(3), 359-390.

Marshall, N. A., Marshall, P. A., Tamelander, J., Obura, D., Malleret-King, D., & Cinner, J. E. (2010). *A Framework for Social Adaptation to Climate Change; Sustaining Tropical Coastal Communities and Industries*. IUCN: Gland, Switzerland.

McCright, A. M., & Dunlap, R. E. (2011). The politicization of climate change and polarization in the American public's views of global warming, 2001-2010. *Sociological Quarterly, 52*(2), 155-194.

Mei, S. L., Weng, C. N., Tan, M. L., Daud, N., Ismail, W. R., & Leng, P. W. (2020). Socio-economic and livelihood assessment of inland fishermen in Muda River Basin. *European Proceedings of Social and Behavioural Sciences*.

Mohan, A., Aswathi, K. R., & Chitra, K. P. (2021). Indigenous farming systems and global sustainability. In W. Leal Filho, A. Marisa Azul, L. Brandli, A. Lange Salvia, P. Gökçin Özuyar, & T. Wall (eds), *Reduced Inequalities. Encyclopedia of the UN Sustainable Development Goals*. Springer, Cham.

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to environmental change: Contributions of a resilience framework. *Annual Review of Environment and Resources, 32,* 395-413.

Nelson, G. C., Rosegrant, M. W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., & You, L. (2010). *Food security, farming, and climate change to 2050: Scenarios, results, policy options (Vol. 172)*. International Food Policy Research Institute.

Nkonya, E., Place, F., Kato, E., & Mwanjololo, M. (2015). Climate risk management through sustainable land management in Sub-Saharan Africa. *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa*, 75-111.

O'Brien, K., & Leichenko, R. (2000). Double exposure: Assessing the impacts of climate change within the context of economic globalization. *Global Environmental Change, 10*(3), 221-232.

O'Brien, K., Hayward, B., & Berkes, F. (2009). Rethinking social contracts: Building resilience in a changing climate. *Ecology and Society, 14*(2).

O'Brien, K., St. Clair, A. L., & Kristoffersen, B. (Eds.) (2010). *Climate Change, Ethics and Human Security*. Cambridge Univ. Press.

OECD (2013). *Economic Well-being*. OECD iLibrary.

OECD (2020). *The Economy of Well-being: Creating Opportunities for People's Well-being and Economic Growth*. OECD Publishing.

Omar, I., Abdullah, R., & Soffie, W. M. (2003). *National report of Malaysia on the formulation of a transboundary diagnostic analysis and preliminary framework of a strategic action programme for the Bay of Bengal*. BOBLME Report, 108.

Osberg, L. (2020). Index of Economic Well-Being. In F. Maggino (Ed.), *Encyclopedia of Quality of Life and Well-Being Research* (pp. 1-6). Springer.

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change, 20*(4), 550-557.

Pelling, M. (2010). *Adaptation to Climate Change: From Resilience to Transformation*. Routledge.

Pelling, M., & High, C. (2005). Understanding adaptation: What can social capital offer assessments of adaptive capacity? *Global Environmental Change, 15*(4), 308-319.

Questa, K., Das, M., King, R., Everitt, M., Rassi, C., Cartwright, C., & Elsey, H. (2020). Community engagement interventions for communicable disease control in low- and lower-middle-income countries: Evidence from a review of systematic reviews. *International Journal for Equity in Health, 19,* 1-20.

Raithel, S., Sarstedt, M., Scharf, S., & Schwaiger, M. (2012). On the value relevance of customer satisfaction. Multiple drivers and multiple markets. *Journal of the Academy of Marketing Science, 40*(4), 509-525.

Rehan, B. M., Bweya, A. Z., Mok, Y. W., Zulkafli, Z., & Raffar, N. (2024). Seasonal flood risk for paddy rice production in northwest Peninsular Malaysia. *Hydrological Sciences Journal, 69*(4), 506-518.

Rehan, B. M., Yusuf, A. M., & Idham, I. L. (2020). Flood risk estimation of paddy production considering plants' age and flood durations. In *Proceedings of AICCE'19: Transforming the Nation for a Sustainable Tomorrow 4* (pp. 1163-1174). Springer International.

Ringle, C. M., Wende, S., & Becker, J.-M. (2024). SmartPLS 4. Bönningstedt: SmartPLS. Retrieved from https://www.smartpls.com

Rizzo, G., Migliore, G., Schifani, G., & Vecchio, R. (2024). Key factors influencing farmers' adoption of sustainable innovations: A systematic literature review and research agenda. *Organic Agriculture, 14*(1), 57-84.

Rodríguez-Barillas, M., Klerkx, L., & Poortvliet, P. M. (2024). What determines the acceptance of Climate Smart Technologies? The influence of farmers' behavioral drivers in connection with the policy environment. *Agricultural Systems, 213,* 103803.

Rogers, E. M. (2003). *Diffusion of Innovations* (5th ed.). Free Press.

Sah, S., Sultan Ali, K., Maulud, K., & Sharil, S. (2021). Impact of saltwater intrusion on paddy growth in Kuala Kedah, Malaysia. *Journal of Sustainability Science and Management, 16*(6), 15-30.

Sattler, C., & Nagel, U. J. (2010). Factors affecting farmers' acceptance of conservation measures—A case study from north-eastern Germany. *Land Use Policy, 27*(1), 70-77.

Schut, M., Klerkx, L., Sartas, M., Lamers, D., Mc Campbell, M., Ogbonna, I., & Leeuwis, C. (2016). Innovation platforms: Experiences with their institutional embedding in agricultural research for development. *Experimental Agriculture, 52*(4), 537-561.

Shaffril, H. A. M., Abu Samah, A., D'Silva, J. L., Sulaiman, & Yassin, S. M. (2013). The process of social adaptation towards climate change among Malaysian fishermen. *International Journal of Climate Change Strategies and Management, 5*(1), 38-53.

Shaffril, H. A. M., Hamzah, A., D'Silva, J. L., Abu Samah, B., & Abu Samah, A. (2017). Individual adaptive capacity of small-scale fishermen living in vulnerable areas towards the climate change in Malaysia. *Climate and Development, 9*(4), 313-324.

Sharifzadeh, M. S., Damalas, C. A., Abdollahzadeh, G., & Ahmadi-Gorgi, H. (2017). Predicting adoption of biological control among Iranian rice farmers: An application of the extended technology acceptance model (TAM2). *Crop Protection, 96,* 88-96.

Shen, Y., Kong, W., Shi, R., Du, R., & Zhao, M. (2023). Farmers' adoption behavior of conservation tillage technology: A multidimensional heterogeneity perspective. *Environmental Science and Pollution Research, 30*(13), 37744-37761.

Shi, R., Yao, L., Zhao, M., & Yan, Z. (2023). The role of climate-adaptive technological innovation in promoting agriculture carbon efficiency: Impact and heterogeneity in economic development. *Environmental Science and Pollution Research, 30*(60), 126029-126044.

Shofiyati, R., Habibie, M. I., Cahyana, D., & Susanti, Z. (2024). Precision farming to achieve sustainable and climate-smart agriculture. In P. Kumar & Aishwarya (Eds.), *Technological Approaches for Climate Smart Agriculture* (pp. 229-248). Cham, Switzerland: Springer International.

Sim, L. M., Onishi, A., Gervais, O., & Chan, N. W. (2018). Comparative research on river basin management in the Sagami River Basin (Japan) and the Muda River Basin (Malaysia). *Resources, 7*(2), 33.

Sishodia, R. P., Ray, R. L., & Singh, S. K. (2020). Applications of remote sensing in precision agriculture: A review. *Remote Sensing, 12*(19), 3136.

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change, 16*(3), 282-292.

Sonka, S., Lee, H., & Shah, S. (2023). The YieldWise approach to post-harvest loss reduction: Creating market-driven supply chains to support sustained technology adoption. *Agriculture, 13*(4), 910.

Soussi, A., Zero, E., Sacile, R., Trinchero, D., & Fossa, M. (2024). Smart sensors and smart data for precision agriculture: A review. *Sensors, 24*(8), 2647.

Sovacool, B. K., Linnér, B. O., & Goodsite, M. E. (2015). The political economy of climate adaptation. *Nature Climate Change, 5*(7), 616-618.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge Univ. Press.

Stiglitz, J. E., Sen, A., & Fitoussi, J. P. (2009). *Report by the Commission on the Measurement of Economic Performance and Social Progress*. Paris: Commission on the Measurement of Economic Performance and Social Progress.

Tan, M. L., Samat, N., Chan, N. W., Lee, A. J., & Li, C. (2019). Analysis of precipitation and temperature extremes over the Muda River Basin, Malaysia. *Water, 11*(2), 283.

Tol, R. S. J. (2009). The economic effects of climate change. *Journal of Economic Perspectives, 23*(2), 29-51.

Tol, R. S. J., Klein, R. J. T., & Nicholls, R. J. (2008). Towards successful adaptation to sea-level rise along Europe's coasts. *Journal of Coastal Research, 24*(2), 432-442.

Tompkins, E. L., & Adger, W. N. (2004). Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society, 9*(2), 10.

Turner, N. J., & Clifton, H. (2009). "It's so different today": Climate change and indigenous lifeways in British Columbia, Canada. *Global Environmental Change, 19*(2), 180-190.

Velandia, M., Rejesus, R. M., Knight, T. O., & Sherrick, B. J. (2009). Factors affecting farmers' utilization of agricultural risk management tools: The case of crop insurance, forward contracting, and spreading sales. *Journal of Agricultural and Applied Economics, 41*(1), 107-123.

Wang, S., Tian, Y., Liu, X., & Foley, M. (2019). How farmers make investment decisions: Evidence from a farmer survey in China. *Sustainability, 12*(1), 247.

Wigboldus, S., Klerkx, L., Leeuwis, C., Schut, M., Muilerman, S., & Jochemsen, H. (2016). Systemic perspectives on scaling agricultural innovations. A review. *Agronomy for Sustainable Development, 36,* 1-20.

Wilmarth, M. J. (2021). Financial and economic well-being: A decade review from Journal of Family and Economic Issues. *Journal of Family and Economic Issues, 42,* 124-130.

World Bank (2010). *World Development Report 2010: Development and climate change*. World Bank Publications.

Wu, H. X., Yan, S. O. N. G., Yu, L. S., & Yan, G. E. (2023). Uncertainty aversion and farmers' innovative seed adoption: Evidence from a field experiment in rural China. *Journal of Integrative Agriculture, 22*(6), 1928-1944.

Wu, L., Hu, K., Lyulyov, O., Pimonenko, T., & Hamid, I. (2022). The impact of government subsidies on technological innovation in agribusiness: The case for China. *Sustainability, 14*(21), 14003.

Yassin, S. M., Abu Samah, A., D'Silva, J. L., Shaffril, H. A. M., & Sahharon, H. (2015). *Well-Being Revisited: A Malaysian Perspective*. Selangor: Universiti Putra Malaysia Publisher.

Yohe, G., & Tol, R. S. J. (2002). Indicators for social and economic coping capacity: Moving toward a working definition of adaptive capacity. *Global Environmental Change, 12*(1), 25-40.

Yoshida, T., Onishi, Y., Kawahara, T., & Fukao, T. (2022). Automated harvesting by a dual-arm fruit harvesting robot. *ROBOMECH Journal, 9*(1), 19.

Young, O. R., King, L. A., & Schroeder, H. (2008). *Institutions and Environmental Change: Principal Findings, Applications, and Research Frontiers*. MIT Press.

Yuen, K. F., Cai, L., Qi, G., & Wang, X. (2021). Factors influencing autonomous vehicle adoption: An application of the technology acceptance model and innovation diffusion theory. *Technology Analysis & Strategic Management, 33*(5), 505-519.

Zainal, Z., Shamsudin, M. N., Mohamed, Z. A., & Alias, E. F. (2014). Assessing the impacts of climate change on paddy production in Malaysia. *Research Journal of Environmental Sciences, 8*(7), 331–341.

Zakaria, A., Alhassan, S. I., Kuwornu, J. K., Azumah, S. B., & Derkyi, M. A. (2020). Factors influencing the adoption of climate-smart agricultural technologies among rice farmers in northern Ghana. *Earth Systems and Environment, 4,* 257-271.