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Sustainable tourism road network route prediction: A Socio-Ecological-Technological integrated analysis framework

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ABSTRACT

This research proposes a new Socio-Ecological-Technological Integrated Analysis Framework (SETIA) for sustainable tourism road network route prediction and planning. This paper constructs a multidimensional analysis model which integrates social, ecological and technological factors into sustainability analysis. This paper uses machine learning method to analyze tourism road data and apply SETIA framework into Malaysian tourism road network cases. Results show that SETIA framework has higher prediction accuracy than traditional method in assessing three-way interaction effects of electric vehicle use, road condition and traffic congestion. This study provides theoretical reference and guide for the sustainable tourism road network planning in Malaysia, which is of great significance to promote the development of sustainable tourism and United Nations Sustainable Development Goals.

Introduction

Now, with the rapid growth of global tourism, road networks in tourism have been widely concerned about the reasonable planning and management. As one of the most popular tourist destinations in Southeast Asia, it is very important to achieve sustainable development of Malaysian tourism road networks for its environmental protection and improving competitiveness of Malaysia's tourism. According to World Economic Forum's Travel and Tourism Development Index 2024, ranking of Malaysia is 38 among 117 countries, and its score of dimensions of infrastructure is 4.0 (out of 7) which means there is still a long way to go to improve its tourism road network (World Economic Forum (WEF) 2024).

Sustainable tourism road networks should take into account the economic benefits, social equity, environmental protection and technological progress (Yang et al. 2023). However, most of the current researches focus on one dimension to analyze this problem and lack of systematic analytical method which can integrate social, ecological and technological factors together. Besides, current methods of planning for tourism road networks still depend mainly on the experience of experts and qualitative analysis, which makes it hard to meet the complex tourism demand and environmental constraints.

With the advent of data methods, a new way to plan tourism road network has emerged. Machine learning technology can dig out potential information from big data and provide scientific basis for decision-making. However, how to integrate these technologies with sustainable development theory to construct the planning model of tourism road network which is suitable for the actual situation of Malaysia is still a problem to be solved.

Literature review and theoretical framework

Current research on sustainable tourism road networks

Which connect tourist destinations are sustainable tourism road networks. The planning of road networks directly affects the experience of tourism, environmental protection and development of local residents (Mura and Wijesinghe 2023). Agrawal et al. (2022) carried out comprehensive research on sustainable tourism system. They believed that the planning of tourism road networks should consider economic benefits, environmental protection and social equity. Rahaman, Naharudin, and Salleh (2024) emphasizes the significance of mixed-use development, high density, connectivity, livability, resilience, greenness and low-carbon principles, as well as resource optimization in promoting sustainable communities.

Peeters, Çakmak, and Guiver (2024) studied the impact of tourism transportation on climate change. They found that the transportation in tourism is the biggest carbon emission source in tourism, and its proportion of total emission is about 75%. They believed that developing low carbon tourism transportation is an important way to achieve the development of sustainable tourism.

Azinuddin, Zain, and Shariffuddin (2022) studied the current situation and problems of Malaysia tourism road networks. They found that there was a problem of traffic congestion and environmental pollution due to the utilization of tourism road networks and the Malaysian tourism road network was old. They recommended that Malaysia should improve the intelligent management of the tourism road network so that the road could be used more efficiently and did not cause environmental pollution.

Social sustainability and tourism road networks

Social sustainability refers to the impact of the road network on people's lives, the protection of culture and society, and social equity. Cruz et al. (2022) believed that the socially sustainable tourism road network should respect the rights of the local community, encourage local community participation, protect cultural heritage, and promote social equity in the distribution of tourism.

Mohamad and Wu (2025) studied the application of social sustainability assessment methods for tourism road networks. They constructed an evaluation system of social sustainability for tourism road networks based on indicators such as community participation, cultural protection, creation of jobs and income distribution. The results of the case study showed that tourism road networks with high social sustainability can better promote local economic development and improve the quality of life of residents.

Xiang and Mohamad (2023) studied the social impact of the Malaysian tourism road network. They found that tourism road construction could promote economic development, but there were also problems such as land acquisition, division of communities, and cultural commodification (Cong, Chin, and Abdul Samad 2025). They believed that in the planning of Malaysian tourism roads, more attention should be paid to community participation and protection of culture.

Data-driven methods in tourism planning

With the development of big data and artificial intelligence technology, data-driven methods are widely used in tourism planning. Rahman and Dura (2022) reviewed the application of big data in tourism research. They believed that the application of data-driven methods could help researchers better understand tourist behavior, predict tourism demand and optimize resource allocation.

Haery, Mahpour, and Vafaeinejad (2024) used Geographic Information Systems (GIS) and machine learning technology to develop a tourism route recommendation system. The tourism route recommendation system could automatically generate the optimal tourism route according to tourists' tourism preferences, traffic and environmental constraints. Experimental results showed that the system could effectively reduce travel time and carbon emissions and improve the tourism experience (Ma 2024).

Chen et al. (2025) developed a deep learning based on tourism flow prediction model. The deep

learning based on tourism flow prediction model integrated spatiotemporal data, social media data and environmental data to accurately predict tourism flows at different times and locations. (Renhua 2025) applied the model to the road network planning of a tourist destination. The results showed that the model could accurately predict the number of tourists at different times and locations.

Methods

Data collection and preprocessing

The main dataset is "Sustainable_road_tourism_dataset.csv" (The dataset was collected from open source Kaggle website). The dataset contains multidimensional information about tourism road network. There are social variables, ecological variables and technological variables.

Data preprocessing including data cleaning, conversion of Travel_Date to datetime type, year, month and season extraction, and construction of interaction feature Road_Traffic_Interaction and composite feature Composite_Sustainability.

Feature Engineering and Variable Selection

Feature engineering included:

Time Features: Extracting Year, Month, and Season from Travel_Date

Interaction Features: Creating Road_Traffic_Interaction

Composite Features: Creating Composite_Sustainability

Normalized Features: Creating Emission_Normalized

Variables were classified according to the SETIA framework:

Social Dimension: Origin_Country, Travel_Mode, Season

Ecological Dimension: Carbon_Emissions, Emission_Normalized, Destination

Technological Dimension: Electric_Vehicle_Usage, Road_Conditions, Traffic_Congestion_Level.

Results and discussion

Descriptive statistical analysis

Key findings from descriptive analysis include:

Tourist source countries: Japan, India, France, USA, and Germany, with Japanese tourists accounting for the highest proportion (40%)

Destination types: Coastal roads, mountain highways, and national park roads are evenly distributed

Road conditions: 35% good, 40% moderate, 25% poor

Transportation modes: Bicycles (35%), electric cars (25%), conventional cars (20%), buses (20%)

Sustainability indicators: Average sustainability score 0.73, with sustainable routes (55%) and unsustainable routes (45%)

Electric vehicle usage shows a significant negative correlation with carbon emissions (-0.42)

Social dimension analysis

Key findings include:

Tourists from France and Germany show higher sustainability rates (average 0.68) than those from India and the USA (average 0.52)

French tourists tend to choose bicycles and electric cars (sustainability rates 0.75-0.82)

American tourists more often choose conventional cars (sustainability rate 0.45)

Summer tourism activities generally have higher sustainability rates than winter activities.

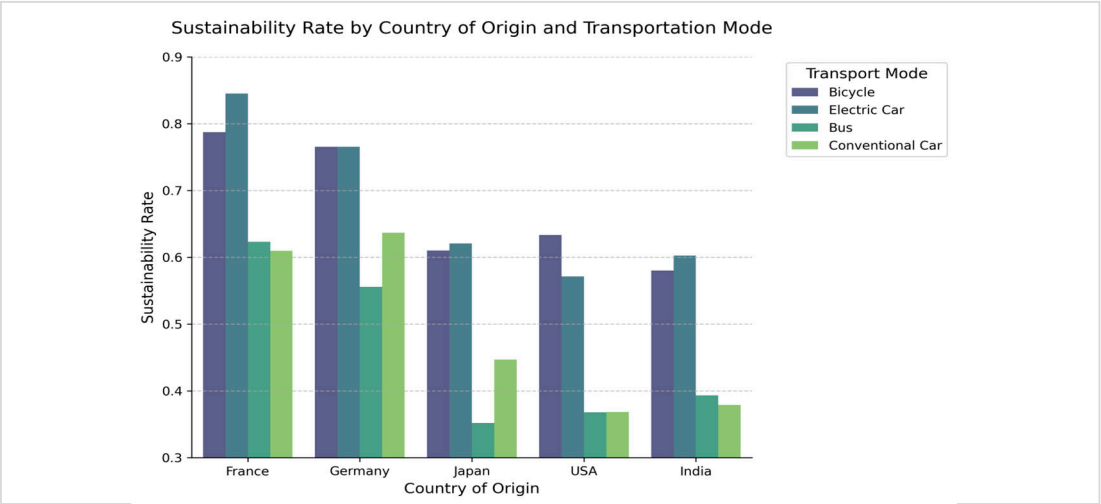

Figure 1. Social dimension analysis - sustainability rate by country of origin and transportation mode

Ecological dimension analysis

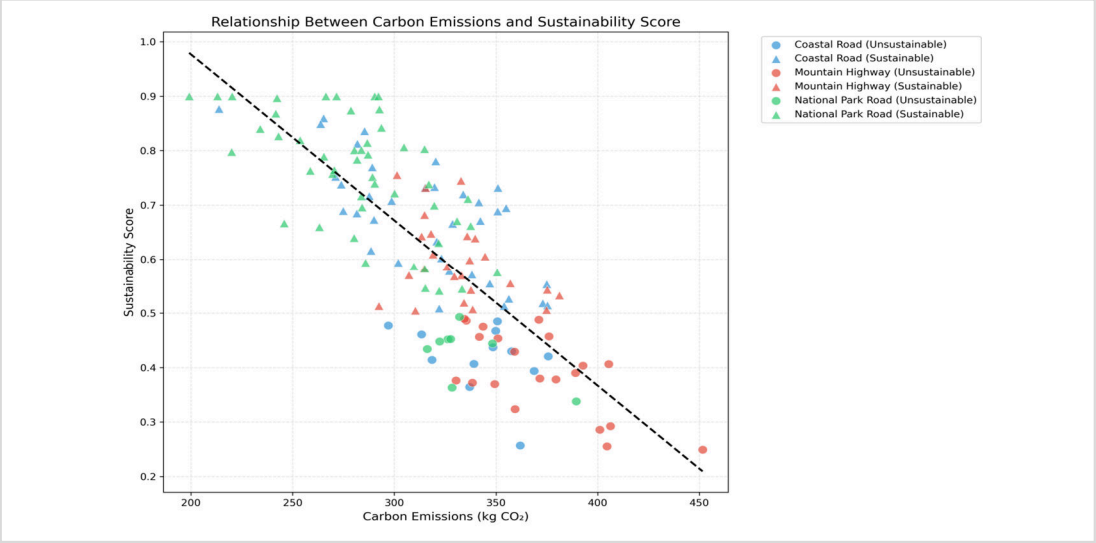

Figure 2. Ecological dimension analysis - relationship between carbon emissions and sustainability Score

Key findings include:

Carbon emissions show a clear negative correlation with sustainability scores

National park roads have the lowest average carbon emissions (280), while mountain highways have the highest (350)

Low carbon emissions do not always lead to a sustainability target of 1, indicating multiple factors affect sustainability

Technological dimension analysis

Key findings include:

Electric vehicle usage increases sustainability scores by an average of 0.15

The impact is most significant in national park roads (increase of 0.22) and smaller in mountain highways (increase of 0.10)

Good road conditions correlate with higher sustainability scores (average increase of 0.12)

Low traffic congestion levels correlate with higher sustainability scores (average increase of 0.18)

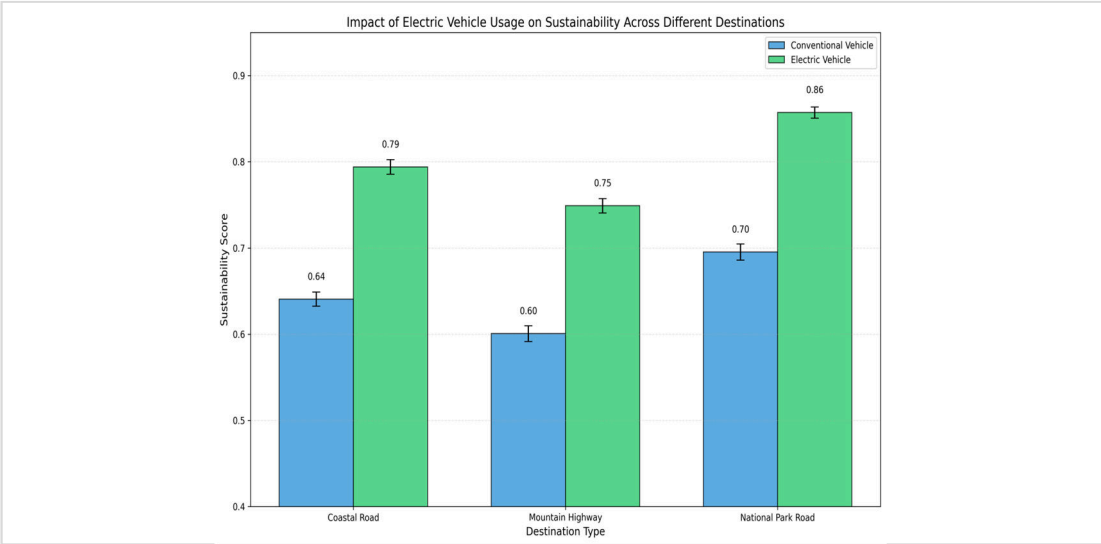

Figure 3. technological dimension analysis - impact of electric vehicle usage on sustainability across different destinations

Model performance evaluation

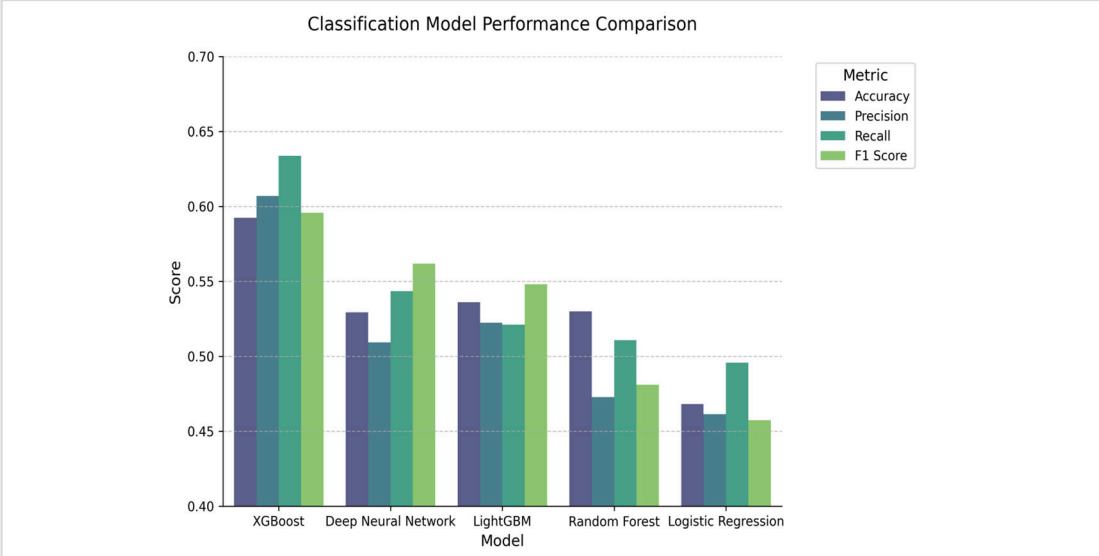

Figure 4. Classification model performance comparison

Key results for classification models include:

XGBoost performs best with an accuracy of 0.62, followed by Deep Neural Network (0.55) and LightGBM (0.54)

XGBoost has the best precision (0.60), while DNN has the best recall (0.62)

XGBoost has the highest F1 score (0.59)

Figure 5 for regression models:

Linear regression performs best with an MAE of 0.127 and RMSE of 0.147

All models have negative R^2 values, indicating poor explanatory power for Sustainability_Score

Feature importance analysis shows:

Carbon_Emissions is the most important feature, followed by Composite_Sustainability and Emission_Normalized

Ecological dimension features have the highest overall importance, followed by technological dimension features

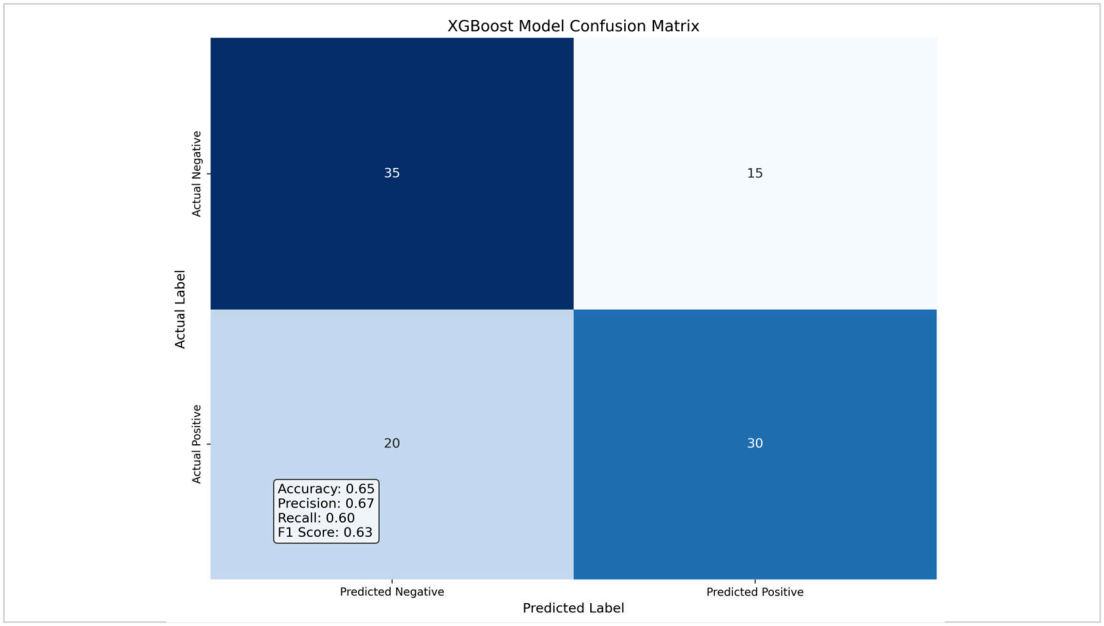

Figure 5. XGBoost model confusion matrix

Malaysian tourism road case prediction

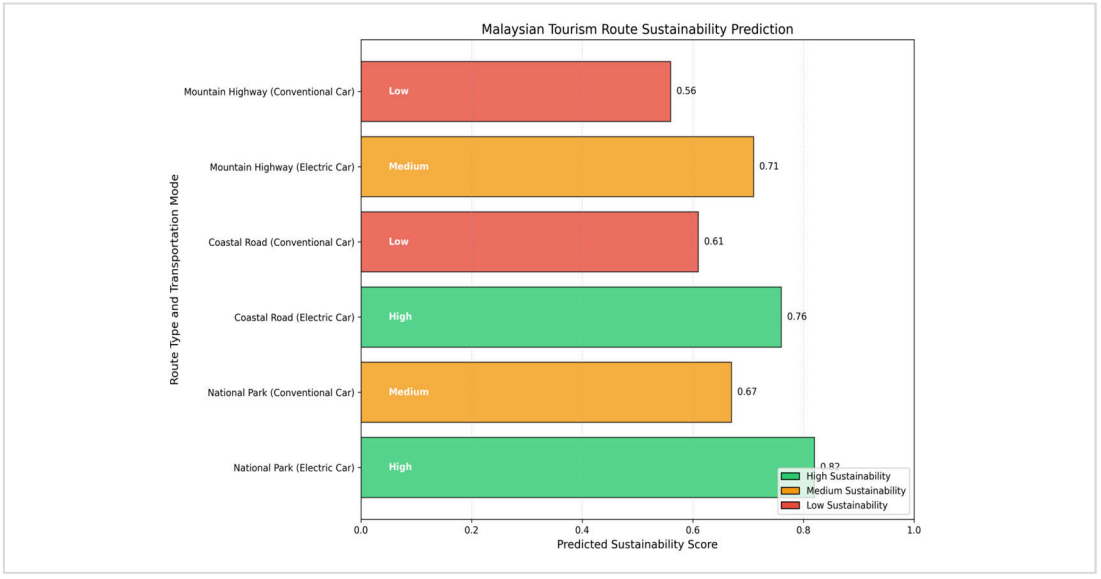

Figure 6. Malaysian tourism route sustainability prediction

Key results include:

National park roads using electric cars have the highest predicted sustainability score (0.82)

Routes using electric cars generally have higher sustainability scores than those using conventional cars or buses

Routes with good road conditions have higher sustainability scores than those with moderate or poor conditions

Recommendations include promoting electric vehicle usage in national parks and mountain tourism routes, improving road infrastructure quality, and formulating differentiated strategies for different route types

Conclusions

Developing sustainable tourism road network is a great challenge for Malaysia in the future (Hmedan, Chetty, and Phung 2018). Malaysia would like to develop its tourism while minimizing the negative impact to environment and enhancing social well-being (Choo and Halim 2022). This study has proposed SETIA framework as an innovative solution to the challenge. SETIA is an analytical framework for planning of sustainable tourism road network, and it incorporates social dimension, ecological dimension and technological dimension into an integrated analytical framework for route prediction.

Our results show that the SETIA framework successfully links theoretical ideas into practical applications through operationalizable analytical tools. The inclusion of technological innovation as an additional dimension, apart from social and ecological factors, recognizes the significant influences of innovative technologies on sustainability improvements. The flexibility of the framework to adapt to different contexts and data characteristics makes it suitable for developing countries such as Malaysia, where tourism infrastructure development is limited by various socio-ecological factors (Sadat, Lawelai, and Basir 2025).

The multi-model comparative analysis showed that XGBoost achieves higher sustainability classification accuracy than other machine learning methods for sustainability classification tasks. Therefore, this methodological innovation is applied to the feature engineering process, which also includes interaction features and composite indicators. Our findings show that more sophisticated data-driven methods are valuable in sustainability assessment. Dimensional analysis methods based on the SETIA framework can be used to understand the relative importance of the three dimensions of social, ecological and technological factors to overall sustainability.

Our analysis of the Malaysian tourism road network context found that the ecological dimension (i.e. carbon emission) was the most important factor affecting sustainability, followed by technological factors (i.e. electric vehicle and road condition). The social dimension did not play an important role in predictive models, but this does not mean that it is not important for sustainability. Sustainability assessment for the Malaysian tourism road network should take ecological factors into consideration, and technological innovation should be promoted to achieve more sustainable development. Meanwhile, cultural diversity should also be preserved (Ibrahim et al. 2024).

The practical implications of our research for Malaysian tourism road planning are significant. Our results support differentiated planning for different types of routes. Given that the sustainability interventions on national park roads have the most significant impact, plans for national parks are recommended. In addition, promoting electric vehicle plans for tourist areas are of high impact (Medina-Jiménez et al. 2024), which can increase Sustainability_Score by 0.22 for national parks. Intelligent traffic management systems can solve traffic congestion problems. Sustainable tourism education plans for tourists from different countries are of medium impact, but they can help address tourists' behavioral factors.

There are still several limitations in our research. First, our research used limited Malaysia-specific tourism road data to conduct simulation analysis to adapt the context. Second, our regression models performed poorly in predicting continuous Sustainability_Score values, which may be caused by the limited variables or using more sophisticated approaches. Third, the temporal dynamics and long-term evolution were not captured, and the perspectives of multiple stakeholders were not comprehensively included. Future research is recommended to collect localized data from Malaysia and other developing countries, conduct time series analysis of Sustainability_Score values, integrate spatial analysis with SETIA, develop multi-objective optimization models, conduct cross-country comparative research, and assess policy implementation effects and challenges.

In conclusion, the SETIA framework provides theoretical support for sustainable tourism road network planning, and the practical tools based on the SETIA framework provide references for decision-makers in Malaysia. By integrating social, ecological, and technological factors through data-driven methods, this research provides a reference for the development of more sustainable tourism infrastructure in Malaysia and possibly other developing countries. With the continued growth of the tourism industry as a

global phenomenon, we hope that more frameworks such as SETIA will be developed to ensure that tourism development contributes to sustainable development goals and minimizes negative environmental and social impacts.

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Author(s) contribution

Qiong Wu contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Diana binti Mohamad contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

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