SINERGI Vol. 28, No. 1, February 2024: 163-168
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2024.1.016

Developing adjustable stiffness for smart material of magnetorheological elastomer to diminish vibration

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Abstract
Many vibration isolators, such as passive vehicle mounting devices, have an inflexible stiffness. This article presents the development of a smart material vibration isolator based on magnetorheological elastomer (MRE), which has adjustable stiffness to minimize unwanted vibrations. The objective of this research is to first create a design for the vibration isolator, and then simulate a magnetic circuit. The Finite Element Method Magnetics (FEMM) software was employed to simulate the effectiveness of the electromagnetic circuit in generating a magnetic field through the vibration isolator by employing MRE samples. Pure iron was chosen as the material for the housing of the vibration isolator test rig. To attain an optimal magnetic field, an inventive design of the magnetic circuit, including examination of the wire type, size, and coil turn number, along with the housing material of the test rig, was performed. The study analyzed the performance of the MRE vibration isolator concerning different current inputs in the coil. The results indicate that the stiffness value of the MRE-based isolator system can be more effectively modified by increasing the current inputs. Therefore, a larger current input leads to a greater change in stiffness.

Keywords:
Isolator;
Magnetorheological Elastomer;
Vibration;

Article History:
Received: August 12, 2023
Revised: November 16, 2023
Accepted: November 18, 2023
Published: February 2, 2024

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INTRODUCTION

A conventional passive system is straightforward, inexpensive, and does not need to require an external power source. In addition, its parameters are generally permanent and selected based on design requirements. It is natural rubber that serves as a suitable material [1, 2, 3]. Due to the permanent characteristics of the rigidity of the material, to reduce vibrations in very restricted frequency, a passive system is efficient. When other forces appear and disrupt the load, it rises and falls from its original position. To overcome the obstacle, many researchers have theoretically and experimentally investigated a wide variety of active and semi-active systems [4, 5, 6, 7, 8, 9]. A semi-active isolation system turns out to be able to change the reducing characteristics of the system even if no actuator is used.

The ability of the active isolation system to inject energy from an external source into the system distinguishes it from the conventional one in its ability to inject energy from an external source into the system. It contributes to giving controlled properties in the active system. A combination of extra parts, including actuators, electronics, and sensors, are combined [10]. However, the active system has its disadvantages; for activation, it needs high power consumption. Therefore, when it comes to vibrations, a semi-active method is preferred as it works well for both low and high frequencies and has better stability and reliability. In the case of high-frequency vibrations, vibration isolators with low stiffness and attenuation are needed, whereas, for low-frequency vibrations, vibration isolators with high stiffness and attenuation are required [2, 7].

Viscoelastic materials are innovative materials that respond to magnetic fields by changing mechanically and rheologically [1, 2, 3]. This substance comprises soft ferromagnetic particles and is a particulate compound such as pure iron and powdery carbonyl iron inserted into polymeric materials. Filler material and elastomers are combined in a specific composition to create the composite material. Filler particles stay in a specific location in the elastomer matrix after the MRE has dried and cured. The magnetorheological (MR) effect is a set of mechanical qualities a particle produces when applying a magnetic field. It results from the particle governing itself and constructing a chain-like structure, as explored by Jobob Rabinow in 1948. Changes in stiffness are another way to spot the MR impact. Hence, several configurations have been tested by adjusting the various parameters (i.e., matrix material, additives, size, percentage content, type, and the shape of the fillers to produce a more effective MRE based on the MR effect [1, 3, 4, 5, 11, 12, 13, 14, 15].

There have been many researchers who studied how to improve the performance of vibration dampers using MRE material [6, 8, 16, 17, 18, 19]. They study performance using magnetic field analysis. Many researchers have produced many papers addressing the limitations of vibration-damping tools that are considered passive in lowering vibration frequency. MRE material offers excellent potential for application as intelligent tools across various engineering disciplines, particularly those involving vibration isolation.

Several studies [9, 20, 21] have proposed by researchers many vibration isolators based on MRE. From previous studies, MREs have been shown to have great potential to be applied for vibration isolation in various stiffness suspension systems. This research uses an intelligent material called magnetorheological elastomers (MRE) for such vibration isolators. It can help reduce unwanted vibrations due to its elastic and damping properties under an external magnetic field. To obtain optimum vibration isolator performance by utilizing MRE materials and appropriate variables such as housing material selection, wire type, wire size, and number of coil turns. The vibration isolator was fabricated to demonstrate the feasibility of the vibration-damping system.

This paper aims to develop a vibration isolator with the MRE material and maximize variables such as housing material selection, type, wire size, and the amount of coil turns to get the optimum performance. The MRE is to be placed in an efficient location showing the highest magnetic flux density concentration. A vibration isolator is fabricated to show the effectiveness of the vibration-dampening system.

MATERIAL AND METHOD

MRE manufacture consists of several materials such as Carbonyl Iron Powder (CIP), silicone oil, and silicone rubber [1, 3, 16, 18, 22]. As shown in Figure 1, the steps for making an MRE generally consist of three steps. The first step is to mix several materials, namely silicone rubber, silicone oil, and micrometer-sized iron carbonyl magnetic particles. Stirring was carried out at room temperature. The second step is mixing CIP into the polymer matrix; during the stirring process, air bubbles will be in it.

Additionally, the MRE sample's air bubbles need to be eliminated. The last step is the mixture of the results of the steps above is poured into a mold of a specific size that has been made, and the sample is left for several hours so that it hardens. After that, the mold is filled with the sample material mixture and polymerized for 2-3 hours at high temperatures (200-500 ^{0}C). At room temperature, it is heated for up to 24 hours.

The MRE samples are then classified as isotropic (CIP random arrangement) or anisotropic (CIP chain) architectures based on the particle distribution. The Anisotropic type occurs during the polymer's final curing process. The iron particles in the sample will form chains once the solidification process is finished and a magnetic field is applied to the composite matrix.

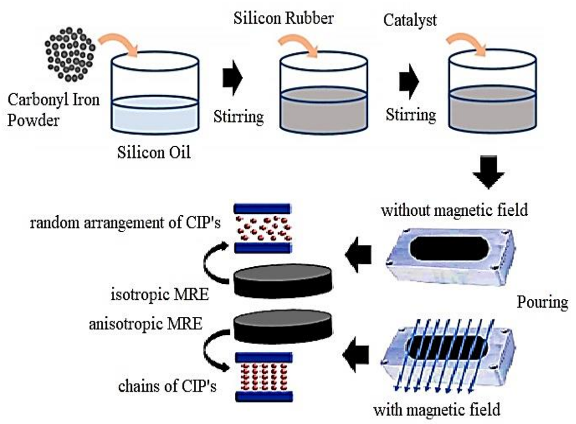

Figure 1. The step-by-step MRE fabrication

In contrast, the Isotropic form occurs when no magnetic field is applied to the sample during the polymer hardening process, so the iron particles in the sample are arranged randomly and irregularly.

Simulation

An easily accessible free, open-source software program called the Magnetic Finite Element Method (FEMM) can be found online. This software application can solve electromagnetic problems for finite element analysis [22, 23, 24, 25, 26]. Additionally, this program can address 2D and 3D colorimetry's linear and nonlinear harmonic low-frequency magnetic issues and linear magnetostatic and electrostatic problems. It also aims to help get the best magnetic circuit design on vibration isolators made of MRE. Various combinations of MRE composition materials were simulated using this application. Various conditions and parameters must be done to make the resulting magnetic field simulation optimal in reducing vibrations. A multi-sandwich arrangement of MRE with pure iron is also carried out, including the number of turns attached to the coil to obtain an optimal magnetic field to induce MRE. The innovation that was carried out was to simulate the MRE arrangement in the middle of the vibration isolator, which consisted of only MRE without a pure iron plate; then, to create a maximum magnetic field, it was also examined whether one steel plate and two steel plates should be put in opposite directions. Figure 2 shows the design drawings and fabricated vibration isolator proposed in this research.

The material for the components of the vibration isolator is chosen based on its ability to produce the strongest magnetic field to induce a uniform cross-sectional area to change the stiffness of the MRE. Pure iron, a good conductor of magnetic fields, was chosen to make vibration isolator housings. The material will be simulated, and which conductor is the best at conducting a simulated magnetic field.

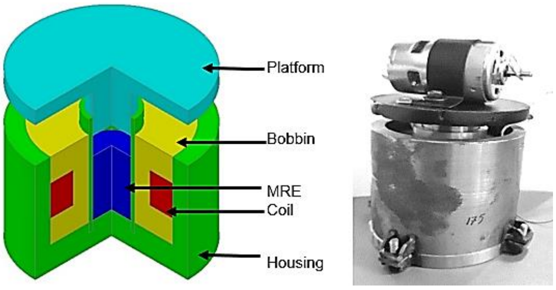

Figure 2. Design and fabrication of vibration isolator

Additionally, tests are performed on the type of wire, its size, the number of coil turns, and the current provided to the coil to produce the best magnetic field generator circuit innovation to counteract the vibrations given to the system. In developing a coil that produces an optimal magnetic field (B), the American Wire Gauge (AWG) 18-wire type is used. When the type of wire is known, various numbers of turns of the coil are made to vary, namely 250, 500, and 1000. The software connects the nodes when the properties and materials blocks for each section are determined. The main objective of this study is for the MRE to be placed in an efficient position, namely the location that shows the highest concentration of magnetic flux density.

Figure 3 shows the contour plot of magnetic flux density on the vibration isolator using FEMM software. For best results, it is necessary to modify the vibration isolator. In the most recent simulation, the vibration isolator coil was subjected to varying currents of various magnitudes, namely 0.5, 1, 1.5, and 2 amperes. Magnetic fields generated by various currents to the coil are shown in Figure 4.

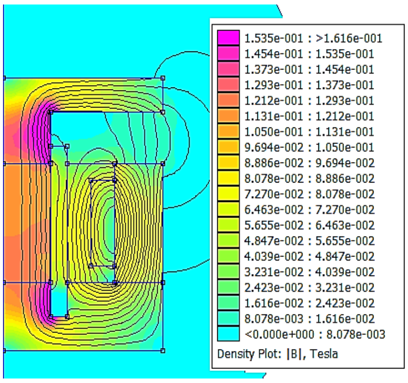

Figure 3. The contour plot of the magnetic flux density

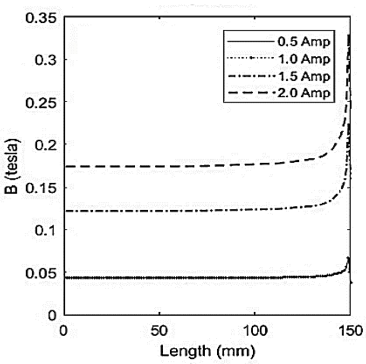

Figure 4. Magnetic fields generated by various current source

RESULTS AND DISCUSSION

The design and experimental test results are used to obtain data on vibration isolators using MRE materials. The test rig used can be shown in Figure 5. The equipment used in this experiment was the SIRIUS mini SIRIUSm-4xACC DAQ system with 4 Dewesoft channels, a piezo-electronic accelerometer PCB®, and a laptop computer. They are connected to the DAQ as a software and hardware interface to send vibration signals to laptops and piezoelectric accelerometers. A DC supply powers the electromagnetic coil within a vibration isolator. As a vibration disturbance in the form of a DC motor placed above the vibration isolator.

This experiment uses a DC motor mounted on a vibration isolator as a generator of vibration. Several voltage sources were supplied constantly with a voltage of 4, 6, and 8 VDC to get various vibrations. During the experiment, the electromagnetic coil had a current of 0.0, 1.0, 1.5, 2.0, and 2.5 amperes, respectively. As the current provided to the electromagnetic coil increases, the magnetic flux density in the vibration isolator's effective area rises. The MRE's stiffness is increased due to the carbonyl iron particles' reaction. This reduces the vibrations generated by the 4, 6, and 8 VDC motors to the MRE vibration isolators. Figure 6-11 shows the data collected from the time response graphs of coherence levels and power spectral density, as well as an analysis of differences of disturbed isolators in vibration amplitudes.

Figure 6, Figure 7 and Figure 8 show the coherence levels for two different signals for two different currents flowing in the vibration oscillator coil. Coherence here measures the degree of linear dependency between the two signals by comparing the similarity of the frequency components of the two signals. The coherence magnitude of two signals is equal to 1 if their frequencies are coordinated. If they are not related, their coherence magnitude is 0.

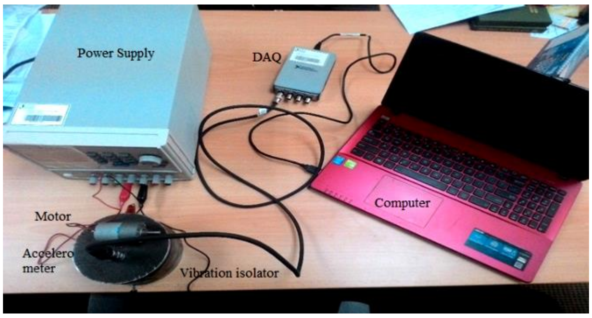

Figure 5. Vibration isolator test rig

Three types of disturbances are given to the vibration isolator by applying input voltages to the motor, namely 4, 6, and 8 volts. Five current types are applied to the vibration-isolating coil to create a magnetic field. It is noticed that the coherence level from 0 amps to 2.5 amps shows the lowest value compared to other signal coherence levels. As the current applied to the vibration isolator coil increases, it will cause the magnetic field to disappear and grow. Thus, the MRE stiffness also increases.

Figure 9, Figure 10 and Figure 11 display the power spectral density for the vibration signal on the MRE-based vibration isolator when three types of disturbances are given to the vibration isolator.

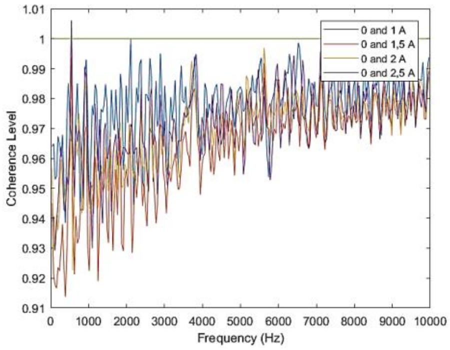

Figure 6. The coherence level for the vibration signal with a 4 VDC voltage of the DC motor

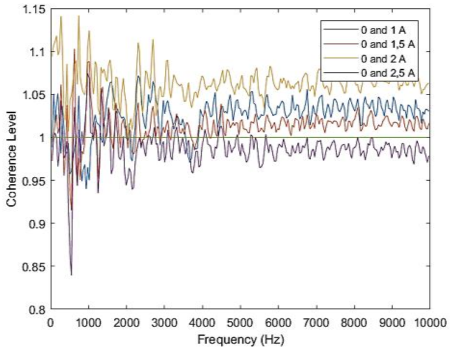

Figure 7. The coherence level for the vibration signal with a 6 VDC voltage of the DC motor

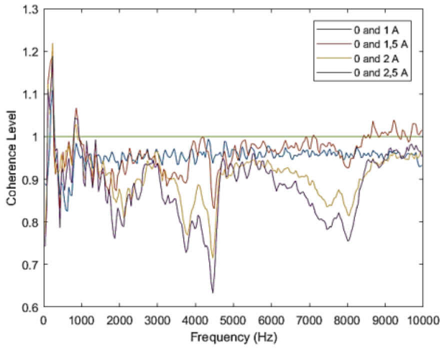

Figure 8. The coherence level for the vibration signal with an 8 VDC voltage of the DC motor

In each disturbance, five types of current are applied to the vibration isolator coil, namely 0, 1, 1.5, 2.0, and 2.5 Amperes. The figures illustrate that the power spectral density value with the minor magnitude is when a current of 0 Ampere is applied to the coil. This means that the stiffness of the MRE has the lowest value. The highest acceleration magnitude value is displayed by the MRE when a current of 2.5 Amperes is applied to the vibration isolator coil, which means the MRE stiffness value is high. It can be concluded that an increase in difference occurs in the vibration amplitude whenever an increase in the current inducing the vibration isolator coil is given.

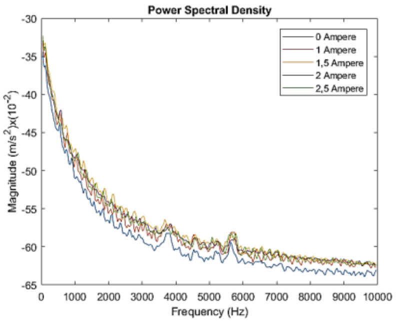

Figure 9. The power spectral density for the vibration signal with a 4 VDC voltage of the DC motor

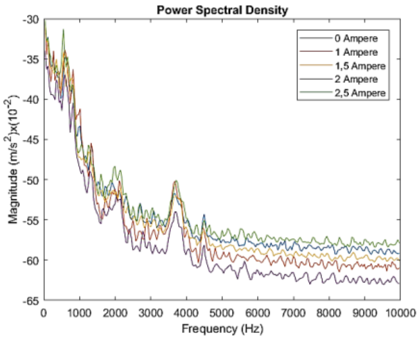

Figure 10. The power spectral density for the vibration signal with a 6 VDC voltage of the DC motor

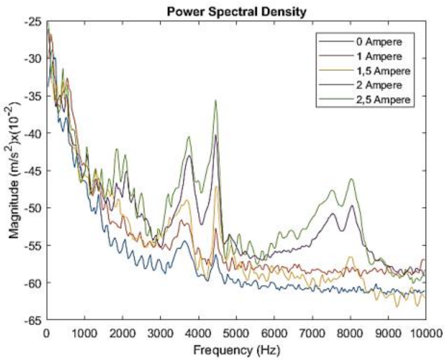

Figure 11. The power spectral density for the vibration signal with an 8 VDC voltage of the DC motor

CONCLUSION

It can be inferred from this research that an MRE-based vibration isolator has been created. The material used as housing is aluminum AISI-1020, and the number of coil turns is 1000 using AWG 18 type wire. The DC motor is a disturbance generator mounted above the vibration isolator functions. The current flowing to the coil varies. According to the experimental findings, as the current applied to the vibration isolation coil grows, an increasing magnitude value for the accelerated amplitude is seen based on the power spectral density graph and signal coherence level. This demonstrates that the stiffness of the vibration isolator, which is adjusted by an external magnetic field created by applying an electric current to the vibration isolator's coil, can alter the MRE properties.

ACKNOWLEDGMENT

The authors intend to express their warmest appreciation towards The Ministry of Education, Culture, Research, and Technology, the Republic of Indonesia, for their full support in this research through the DRTPM research grant under PKDN Universitas Widyagama Malang, Indonesia.

REFERENCES

[1] A. K. Bastola and M. Hossain, "A Review on Magneto-Mechanical Characterizations of Magnetorheological Elastomers," *Composites Part B: Engineering*, vol. 200, p. 108348, Nov. 2020, doi: 10.1016/j.compositesb.2020.108348.

[2] Ubaidillah et al., "Recent Progress on Magnetorheological Solids: Materials, Fabrication, Testing, and Applications," *Adv. Eng. Mater.*, vol. 17, no. 5, pp. 563–597, May 2015, doi: 10.1002/adem.201400258.

[3] S. R. Kumbhar, S. Maji, and B. Kumar, "Automotive Vibration and Noise Control using Smart Materials: A State of Art and Challenges," *World Journal of Engineering*, vol. 11, no. 4, pp. 413–420, Aug. 2014, doi: 10.1260/1708-5284.11.4.413.

[4] S. U. Khayam et al., "Development and Characterization of a Novel Hybrid Magnetorheological Elastomer Incorporating Micro and Nano Size Iron Fillers," *Materials & Design*, vol. 192, p. 108748, 2020.

[5] C. Liu et al., "Development and control of magnetorheological elastomer-based semi-active seat suspension isolator using adaptive neural network," *Frontiers in Materials*, vol. 7, p. 171, 2020.

[6] T. Jin *et al.*, "Development and evaluation of a versatile semi-active suspension system

for high-speed railway vehicles," *Mechanical Systems and Signal Processing*, vol. 135, p. 106338, 2020.
[7] A. Ali et al., "Development of a performance-enhanced hybrid magnetorheological elastomer-fluid for semi-active vibration isolation: Static and dynamic experimental characterization," *Materials*, vol. 15, no. 9, p. 3238, 2022.
[8] J. Kumar and G. Bhushan, "Dynamic analysis of quarter car model with a semi-active suspension based on the combination of magneto-rheological materials," *International Journal of Dynamics and Control*, vol. 11, no. 2, pp. 482–490, 2023.
[9] Y. Choi and N. M. Wereley, "Vibration isolation performance of an adaptive magnetorheological elastomer-based dynamic vibration absorber," presented at the Actuators, MDPI, 2022, p. 157.
[10] G. Priyandoko, M. Mailah, and H. Jamaluddin, "Vehicle Active Suspension System using Skyhook Adaptive Neuro Active Force Control," *Mechanical Systems and Signal Processing*, vol. 23, no. 3, pp. 855–868, 2009.
[11] B. Siagian et al., "Chronic Lower Back Pain and Its Relationship with Vibration Exposure and Sitting Duration; A Cross-Sectional Study Among Commercial Motorcycle Driver," *The Indonesian Journal of Community and Occupational Medicine*, vol. 1, no. 3, pp. 154–61, 2022.
[12] M. A. Shaid Sujon et al., "Damping and Sound Absorption Properties of Polymer Matrix Composites: a Review," *Polymer Testing*, vol. 104, p. 107388, Dec. 2021, doi: 10.1016/j.polymertesting.2021.107388.
[13] M. H. A. Khairi *et al.*, "Enhancement of Magneto-Induced Modulus by the Combination of Filler and Plasticizer Additives-Based Magnetorheological Elastomer," *Materials*, vol. 15, no. 18, p. 6396, 2022.
[14] Y. Zhao and G. Meng, "A bio-inspired semi-active vibration isolator with variable-stiffness dielectric elastomer: Design and modeling," *Journal of Sound and Vibration*, vol. 485, p. 115592, 2020.
[15] D. Leng et al., "A physical model of magnetorheological elastomer isolator and its dynamic analysis," *Journal of Intelligent Material Systems and Structures*, vol. 31, no. 9, pp. 1141–1156, 2020.
[16] Z. Chen *et al.*, "Investigation of a new metamaterial magnetorheological elastomer isolator with tunable vibration bandgaps," *Mechanical Systems and Signal Processing*, vol. 170, p. 108806, 2022.
[17] D. Lin et al., "A new vibration isolator integrating tunable stiffness-damping and active driving properties based on radial-chains magnetorheological elastomer," *Mechanical Systems and Signal Processing*, vol. 183, p. 109633, 2023.
[18] X. B. Nguyen et al., "Novel semiactive suspension using a magnetorheological elastomer (MRE)-based absorber and adaptive neural network controller for systems with input constraints," *Mechanical Sciences*, vol. 11, no. 2, pp. 465–479, 2020.
[19] X. Guan et al. "Semi-active control for benchmark building using innovative TMD with MRE isolators," *International Journal of Structural Stability and Dynamics*, vol. 20, no. 06, p. 2040009, 2020.
[20] M. A. Abdelkareem *et al.*, "Vibration Energy Harvesting in Automotive Suspension System: A Detailed Review," *Applied Energy*, vol. 229, pp. 672–699, 2018.
[21] Y. Yu et al., "Nonlinear characterization of magnetorheological elastomer-based smart device for structural seismic mitigation," *International Journal of Smart and Nano Materials*, vol. 12, no. 4, pp. 390–428, 2021.
[22] N. S. Sobri et al., "Isotropic and Anisotropic Polarizations of Magnetorheological Elastomer," *Zulfaqar Journal of Defence Science, Engineering & Technology*, vol. 6, no. 1, 2023.
[23] B. W. Lenggana, "Finite Element Magnetic Method for Magnetorheological Based Actuators," in *Finite Element Methods and Their Applications*, IntechOpen, 2020.
[24] M. A. M. Fakhree et al., "Simulation of a Pre-structure Device for Fountain-like Magnetorheological Elastomer via Finite Element Magnetic Method (FEMM)," *Journal of Advanced Vehicle System*, pp. 1–7, 2021.
[25] G. Priyandoko and P. Suwandono, "Development of Vibration Isolator Using Magnetorheological Elastomer Material Based," *Journal of Applied Engineering Science*, vol. 19, no. 4, pp. 1108–1113, 2021.
[26] A. Sastranegara, K. E. Putra, E. Halawa, N. A. Sutisna, A. Topa, "Finite Element Analysis on ballistic impact performance of multi-layered bulletproof vest impacted by 9 mm bullet," *SINERGI,* vol. 27, no. 1, pp. 15-22, 2023, doi: 10.22441/sinergi.2023.1.003