International Journal of Multidisciplinary Research and Technology
ISSN 2582-7359, Peer Reviewed Journal, Impact Factor 6.325
www.ijmrtjournal.com

A COMPREHENSIVE REVIEW OF DRY FLOOD AND MQL MACHINING FOR SUSTAINABLE MANUFACTURING

[1]Padhiyar Krushnakant Shivabhai, [2]Prof. Suneel Kumar
[1]M.Tech Student, [2]Assistant Professor, Department of Mechanical Engineering
Vikrant University, Gwalior MP

ABSTRACT

The principle of sustainable machining involves reducing consumption of resources, impacts on environment, and cost of operation without compromising the performance of machining. In this review, the machining processes of dry machining, flood machining, and MQL are compared with respect to machining performance, environmental impact, and economic sustainability of the three machining processes. The important parameters that have been taken into consideration in making the comparison include: cutting temperature, cutting forces, tool wear, surface roughness, productivity, energy consumption, waste, emission, and machining cost. Dry machining does not involve use of cutting fluids; however, it may result in high thermal loading and increased wear of tool. Flood machining provides cooling; however, it needs high fluid consumption and disposal.

Keywords: Sustainable machining, Dry machining, Flood machining, MQL, Tool wear, Cutting temperature, Surface roughness, Environmental sustainability.

1. INTRODUCTION

Sustainable manufacturing has become an essential strategy for minimizing the ecological footprint of manufacturing activities while ensuring that the products retain their quality and productivity. Sustainable manufacturing entails effective use of raw materials, energy, water, and other resources during manufacturing activities coupled with minimizing wastage and emissions. Various types of manufacturing processes are employed; however, machining is commonly used in manufacturing parts with high accuracy and surface finish.

1.1 Sustainable Manufacturing and the Need for Sustainable Machining

Machining operations based on traditional approaches often result in huge electrical power consumption and usage of cutting fluids, as well as production of metal chips, hazardous wastes, aerosols, and other undesirable outputs that have negative impact on environment [1]. Large amounts of traditional cutting fluids used in machining help to achieve good lubrication and cooling, but buying, storing, maintaining, reusing, and disposing of such fluids lead to high expenses and may cause problems related to environment and occupational health [2]. Excessive usage of cutting fluids and energy intensive machining operations also lead to increased environmental impact of manufacturing operations. Therefore, it is necessary to develop sustainable machining approaches that will provide good balance between performance, resource consumption, environmental protection, and cost-effectiveness [3]. Sustainable machining aims to decrease resource consumption and waste production without reducing such characteristics as tool wear, surface quality, productivity, and dimensional accuracy [4].

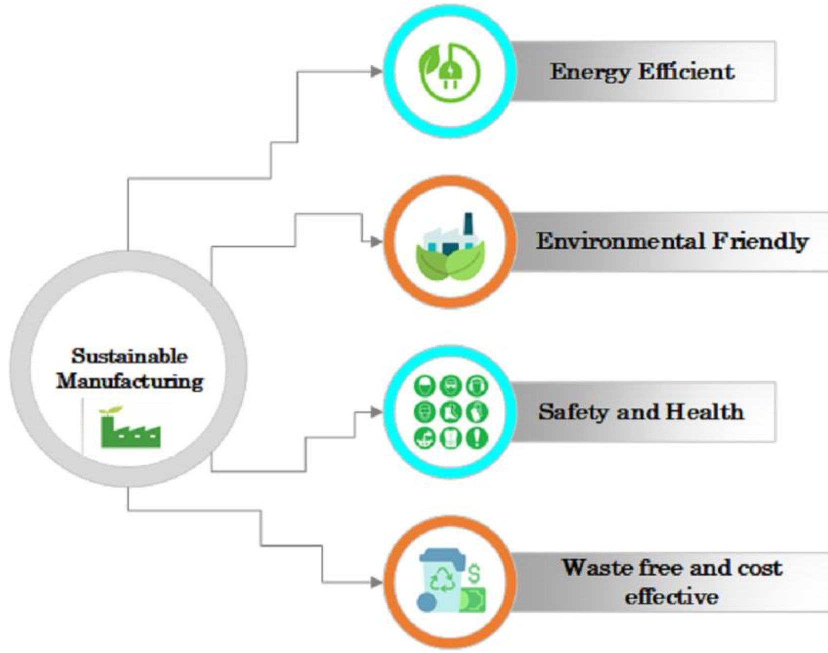

Figure. 1: Key dimensions of sustainable manufacturing.

1.2 Dry, Flood and Minimum Quantity Lubrication Machining

The choice of the right technique of cooling and lubrication greatly influences the machining efficiency and sustainability. Flood cooling and lubrication works well in terms of providing sufficient cooling and lubrication but it consumes a lot of cutting fluid, making it costly, wasteful, and less environmentally friendly [5]. The dry machining method eliminates the use of cutting fluid but may result in an increase in cutting temperature, friction, and tool wear.

Minimal quantity lubrication can be viewed as a compromise between the two techniques in the sense that it applies a minimal amount of lubricant at the cutting region. It conserves the fluid while still offering sufficient lubrication and machining efficiency. Its efficiency is dependent on several factors including the lubricant quality, feed rates, cutting conditions, tool geometry, and workpiece material [6]. Comparison of the three methods of machining is thus important.

1.3 Objectives of the study

The objectives of this review are:

1. To critically review the principles, mechanisms, advantages, and limitations of dry, flood, and MQL machining techniques for sustainable manufacturing.
2. To comparatively evaluate the machining performance of these techniques in terms of cutting temperature, cutting forces, tool wear, tool life, surface roughness, and productivity.
3. To assess their environmental and economic sustainability based on cutting-fluid consumption, energy use, waste generation, occupational safety, and machining cost.
4. To identify research gaps and future opportunities for the development and implementation of advanced sustainable machining techniques.

2. MACHINING TECHNIQUES FOR SUSTAINABLE MANUFACTURING

Heat is generated through machining, making cooling and lubrication necessary in order to control the issues of temperature, wear of tools, and surface finish [7]. Although flood machining is effective due to high volumes of coolant used, the cost incurred, wastage, and environmental concerns have made it unpopular compared to dry machining and minimum quantity lubrication. The former does not use any coolant while the latter uses only little amounts of lubricant.

2.1 Dry Machining

Dry machining is done without the use of conventional cutting fluids, hence no coolant usage, fluid disposal, and coolant management considerations [8]. This type of machining is environmentally friendly and economical and makes chip management easier. However, due to the lack of coolant and lubrication in dry machining, temperatures generated in machining may be higher than those in conventional machining, hence increased wear. For this reason, suitable materials and tool settings are essential [9].

2.2 Flood Machining

Flood machining is the process in which cutting fluid is supplied in larger amounts to the cutting zone continuously to cool down the tool, provide lubrication, and remove the chips. Flood machining ensures proper temperature control, reduces friction and wear and tear of the tools, and enhances the life of tools along with surface finish and stability [10]. However, increased use of cutting fluid in the process is associated with high cost of operations, high maintenance, waste production, and environmental hazards.

2.3 Minimum Quantity Lubrication Machining

MQL is a dry machining method in which only a little amount of lubricant is supplied at the point of cutting, typically in the form of aerosol in the compressed air stream. It mainly helps in reducing friction and adhesion, hence increases the life of tools, machining operation, and surface finish with a reduced amount of fluid use and waste. MQL is a combination of both dry and flood machining methods and has become more attractive with the help of lubricants made from biodegradable vegetable oils. The cooling action of MQL is relatively less when compared to flood machining; therefore, it depends upon several factors.

2.4 Comparative Characteristics of Dry, Flood and MQL Machining

The three machining approaches differ in their cooling and lubrication methods. Flood machining provides effective cooling but uses large quantities of cutting fluid, dry machining eliminates cutting fluids but may increase thermal and wear-related problems, while MQL uses a small amount of lubricant to balance machining performance and resource consumption. Their comparative characteristics are presented in Table 1.

Table 1. Comparative characteristics of dry, flood and MQL machining

Parameter	Dry Machining	Flood Machining	MQL Machining
Cooling medium	No external cutting fluid	Large quantity of cutting fluid	Small quantity of lubricant with compressed air
Lubrication	Very limited	High	Good localized lubrication
Cooling capability	Low	High	Moderate/limited
Cutting-fluid consumption	None	High	Very low
Cutting temperature	Generally higher	Effectively controlled	Generally lower than dry machining
Tool wear	May be high under severe conditions	Generally controlled	Generally lower than dry machining
Tool life	May decrease under high thermal loads	Generally high	Generally improved
Surface quality	May deteriorate under severe conditions	Generally good	Generally good when optimized
Waste generation	Very low	Relatively high	Low
Coolant disposal	Not required	Required	Minimal
Environmental	Low fluid-related impact	Comparatively high	Comparatively low

impact			
Operating cost	Low fluid-related cost	High due to fluid management	Relatively low
System requirements	Simple	Pumping, filtration and circulation system	MQL delivery system and compressed air
Major limitation	High temperature and friction	High fluid consumption and disposal	Limited cooling capability
Sustainability potential	High	Comparatively low	High

3. COMPARATIVE MACHINING PERFORMANCE

The choice of cooling and lubrication techniques is directly related to the machining process efficiency and sustainability [11]. Flood machining is a good technique for providing cooling, but it requires large amounts of fluid, dry machining does not require any cutting fluid but increases the friction and heat generation, while MQL lowers the fluid requirement due to lubrication. Their performances can be compared on the basis of factors like cutting temperature, force, etc [12].

- **Cutting temperature:** Dry machining generally produces higher temperatures because no external coolant is supplied. Flood machining provides the strongest cooling, while MQL reduces temperature mainly by decreasing friction, although its cooling capacity remains lower than flood machining.
- **Cutting forces:** Dry machining may produce higher cutting forces because of increased friction and adhesion. Flood machining reduces friction through cooling and lubrication, while MQL can also reduce cutting forces through localized lubrication at the cutting interface.
- **Tool wear and tool life:** Dry machining can accelerate tool wear due to increased temperature and friction. Flood machining generally provides better tool protection through combined cooling and lubrication. MQL can improve tool life by reducing friction and adhesion, although its effectiveness may decrease under extremely high-temperature conditions.
- **Surface roughness and surface integrity:** Dry machining may result in poorer surface quality under severe thermal and wear conditions. Flood machining generally provides stable surface quality, while optimized MQL can produce surface roughness comparable to or better than dry machining by reducing friction, adhesion, and tool wear.
- **Material removal rate and productivity:** MRR is mainly influenced by cutting speed, feed rate, and depth of cut. Flood machining can generally support demanding cutting conditions, while MQL can provide a balance between productivity and reduced resource consumption. Dry machining can achieve high productivity when suitable tools and parameters are selected, but excessive heat and tool wear may limit performance.
- **Influence of machining parameters:** Cutting speed strongly affects temperature, tool wear, and power consumption, while feed rate influences cutting forces, surface roughness, and MRR. Depth of cut affects material removal, cutting forces, and power requirements. Tool geometry, tool material, coatings, lubricant properties, MQL flow rate, air pressure, and nozzle position also influence overall machining performance.

Overall, flood machining generally provides the best cooling and tool protection, dry machining offers the advantage of eliminating cutting fluids, and MQL provides a balance between machining performance and reduced resource consumption [13].

Table 2: Summary of Previous Research on Dry, Flood and MQL Machining for Sustainable Manufacturing

Author, Year	Topic Covered	Title of the Study
Race et al. (2021) [14]	The study investigated environmentally sustainable cooling strategies during the milling of SA516 steel. It compared dry, flood, and MQL machining conditions and examined their effects on surface integrity and machining performance.	*Environmentally sustainable cooling strategies in milling of SA516: Effects on surface integrity of dry, flood and MQL machining*

Singh et al. (2016) [15]	The study reviewed near-dry machining and MQL techniques applied to difficult-to-machine alloys. It discussed the principles, benefits, limitations, machining performance, and sustainability aspects of MQL-based machining.	*A review of near dry machining/minimum quantity lubrication machining of difficult to machine alloys*
Makhesana et al. (2024) [16]	The study investigated the machinability of Ti-6Al-4V titanium alloy under dry, flood, MQL, and nanofluid-MQL conditions using textured cutting tools. It evaluated the influence of lubrication conditions on machining performance.	*Machinability investigation of Ti-6Al-4V titanium alloy under dry, flood, MQL and nanofluid-MQL techniques using textured tools*
Hassan (2022) [17]	The study conducted a comparative life-cycle analysis of sustainable lubrication techniques. It evaluated environmental impacts together with machining performance to assess the overall sustainability of different lubrication strategies.	*Comparative life cycle analysis of environmental and machining performance under sustainable lubrication techniques*
Khatri and Jahan (2018) [18]	The study investigated tool-wear mechanisms during machining of Ti-6Al-4V under flood coolant, dry, and MQL conditions. It compared the effects of different lubrication conditions on tool wear and associated machining behavior.	*Investigating tool wear mechanisms in machining of Ti-6Al-4V in flood coolant, dry and MQL conditions*

4. ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY

Sustainability of the environment and economy is one of the key criteria in assessing the machining operations [19]. While flood machining offers better cooling capacity, it uses higher amounts of cutting fluid than both dry and minimum quantity lubricant (MQL) machining [20]. Thus, all these approaches have to be evaluated according to their fluid consumption, energy usage, waste production, and other factors [21].

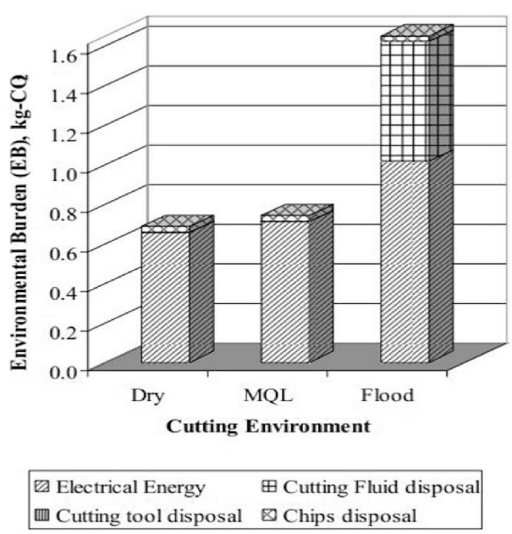

Figure 2: Comparison of environmental burden under dry, MQL and flood machining conditions.

4.1 Cutting-Fluid Consumption

Dry machining consumes zero amount of conventional cutting fluid, hence is resource efficient [22]. Flood machining needs comparatively high amounts of cutting fluids, which makes consumption more than in MQL [23]. MQL involves the use of very little amount of lubricants that are applied to the machining process at the point of cut only, hence lowering the fluid consumption. Hence, MQL is the most efficient option for use when full dry machining is not possible [24].

4.2 Energy Consumption

The energy consumption will include the energy that is used for material removal, along with other factors such as the energy required by the coolant pump, filter, and compressed air [25]. In case of flood machining, there will be additional need of energy to circulate and filter coolant, while in dry machining, this will not be needed [26]. In MQL too, there will be savings in energy use for coolant circulation, but still compressed air will be needed for lubrication [27].

4.3 Waste Generation and Disposal

Dry machining creates very little waste in terms of fluids, while the chips created are very clean and easily recyclable [28]. In flood machining, there is the creation of used cutting fluids, dirty chips, and filters among others that require proper disposal. MQL greatly decreases fluid waste because of the small number of lubricants used. Dry machining and MQL are therefore better than flood machining in waste management [29].

4.4 Occupational Health and Safety

Occupational issues in connection with cutting fluid may arise through skin contact, splash and aerosol formation from cutting fluid [30]. In dry machining, there is no issue of skin contact with the conventional cutting fluid since there is no use of such cutting fluid. However, the problem of dust and hot chips generated during machining process remains to be handled. Flood machining involves higher exposure to coolant and coolant aerosol.

4.5 Carbon Emissions and Environmental Impact

Environmental effects of machining depend on electricity usage, cutting fluid manufacturing, transportation, application, and disposal. While dry machining can lower the environmental effects related to the use of fluids, as no coolant is used, flood machining has larger environmental effects due to its fluid usage and its processing and disposal. MQL is able to lower the effect of machining on the environment because of low fluid usage, especially if the biodegradable or vegetable-oil-based fluid is used.

4.6 Machining and Operating Costs

Costs of machining include costs associated with power, tooling, cutting fluid, maintenance, waste disposal, and equipment costs. Dry machining is cheaper in terms of cooling but may be expensive in terms of tooling if higher wear rate of tools is experienced. Flood machining has long tool life and high production rates but it is very costly in terms of buying, maintaining, and disposing the coolant. MQL is more expensive initially for purchasing the delivery system and compressed air but it saves on lubricant, waste management, and maintenance.

5. CONCLUSION

The conclusion drawn from this review is that dry, flood, and MQL machining methods each had unique strengths and weaknesses for sustainable machining processes. Dry machining involved less use of cutting fluids and produced less waste, but would lead to increased temperatures and wear on tools, whereas flood machining would provide better cooling and machining process performance but would consume more cutting fluids and would have negative environmental effects. MQL machining gave the best of both worlds by reducing lubricant use while still providing adequate tool life and surface finish.

REFERENCES

1. Race, A., Zwierzak, I., Secker, J., Walsh, J., Carrell, J., Slatter, T., & Maurotto, A. (2021). Environmentally sustainable cooling strategies in milling of SA516: Effects on surface integrity of dry, flood and MQL machining. Journal of Cleaner Production, 288, 125580.
2. Singh, T., Singh, P., Dureja, J. S., Dogra, M., Singh, H., & Bhatti, M. S. (2016). A review of near dry machining/minimum quantity lubrication machining of difficult to machine alloys. International journal of Machining and Machinability of Materials, 18(3), 213-251.
3. Makhesana, M., Patel, K., & Bagga, P. (2024). Machinability investigation of Ti-6Al-4V titanium alloy under dry, flood, MQL and nanofluid-MQL techniques using textured tools. Advances in Materials and Processing Technologies, 10(4), 3202-3215.
4. Hassan, K. (2022). Comparative life cycle analysis of environmental and machining performance under sustainable lubrication techniques. Hybrid Advances, 1, 100004.

5. Khatri, A., & Jahan, M. P. (2018). Investigating tool wear mechanisms in machining of Ti-6Al-4V in flood coolant, dry and MQL conditions. Procedia Manufacturing, 26, 434-445.
6. Ghatge, D., & Ramanujam, R. (2023). Sustainable machining: a review. Materials Today: Proceedings.
7. Sandhu, P., Goindi, G. S., & Chopra, S. (2022). Evaluation of dry machining, air-cooling conditions and MQL techniques as sustainable manufacturing processes for turning of aluminium 6061. Materials Today: Proceedings, 68, 791-798.
8. Singh, G., Aggarwal, V., & Singh, S. (2020). An outlook on the sustainable machining aspects of minimum quantity lubrication during processing of difficult to cut materials. Materials Today: Proceedings, 33, 1592-1598.
9. Dawood, A., Arbuckle, G. K., & Jahan, M. P. (2015). A comparative study on the machinability of Ti-6Al-4V using conventional flood coolant and sustainable dry machining. International Journal of Machining and Machinability of Materials, 17(6), 507-528.
10. Khanna, N., & Shah, P. (2020). Comparative analysis of dry, flood, MQL and cryogenic CO2 techniques during the machining of 15-5-PH SS alloy. Tribology International, 146, 106196.
11. Dennison, M. S., Jebabalan, K., Neelavannan, M., & Meji, M. A. (2022). Advances in MQL Machining. Advances in Sustainable Machining and Manufacturing Processes, 71-89.
12. Lopes, J. C., Talon, A. G., Rodrigues, M. D. S., Moretti, G. B., Machado, F. D. C., Souza, G. G. D., ... & Bianchi, E. C. (2023). An experimental evaluation between pure and diluted MQL versus flood lubri-cooling focused on cost and environmental impact. The International Journal of Advanced Manufacturing Technology, 129(5), 2691-2705.
13. Gajrani, K. K., Suvin, P. S., Kailas, S. V., & Sankar, M. R. (2019). Hard machining performance of indigenously developed green cutting fluid using flood cooling and minimum quantity cutting fluid. Journal of cleaner production, 206, 108-123.
14. Debnath, S., Reddy, M. M., & Pramanik, A. (2018). Dry and near-dry machining techniques for green manufacturing. In Innovations in Manufacturing for Sustainability (pp. 1-27). Cham: Springer International Publishing.
15. Yaqoob, S., Ghani, J. A., Juri, A. Z., Muhamad, S. S., Haron, C. H. C., & Jouini, N. (2024). A review of sustainable hybrid lubrication (Cryo-MQL) techniques in machining processes. The International Journal of Advanced Manufacturing Technology, 131(1), 151-169.
16. Khatri, A., & Jahan, M. P. (2020). Investigating the microstructure and morphology of chips in dry, flood coolant and MQL machining of Ti-6Al-4V alloy. International Journal of Sustainable Manufacturing, 4(2-4), 234-250.
17. Vishnu, A. V., Kumar, P. J., & Ramana, M. V. (2018). Comparison among dry, flooded and MQL conditions in machining of EN 353 steel alloys-an experimental investigation. Materials Today: Proceedings, 5(11), 24954-24962.
18. Li, D., Zhang, T., Zheng, T., Zhao, N., & Li, Z. (2024). A comprehensive review of minimum quantity lubrication (MQL) machining technology and cutting performance. The International Journal of Advanced Manufacturing Technology, 133(5), 2681-2707.
19. Sharma, A., & Kumar, R. (2021). Potential use of minimum quantity lubrication (MQL) in machining of biocompatible materials using environment friendly cutting fluids: An overview. Materials Today: Proceedings, 45, 5315-5319.
20. Sen, B., Mia, M., Krolczyk, G. M., Mandal, U. K., & Mondal, S. P. (2021). Eco-friendly cutting fluids in minimum quantity lubrication assisted machining: a review on the perception of sustainable manufacturing. International Journal of Precision Engineering and Manufacturing-Green Technology, 8(1), 249-280.
21. Khan, M. A., Ahmad, R., Jaffery, S. H. I., Butt, S. I., Khan, M. S., & Zahid, D. (2025). Sustainability analysis of tool wear, energy efficiency, surface quality, and energy during dry, MQL, and wet turning of Inconel 718. International Journal of Sustainable Energy, 44(1), 2515447.
22. Tamang, S. K., Chandrasekaran, M., & Sahoo, A. K. (2018). Sustainable machining: an experimental investigation and optimization of machining Inconel 825 with dry and MQL approach. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40(8), 374.
23. Ross, N. S., Ananth, M. B. J., Jafferson, J. M., Rajeshkumar, L., & Kumar, M. S. (2024). Performance assessment of vegetable oil–based MQL in milling of additively manufactured AlSi10Mg for sustainable production. Biomass Conversion and Biorefinery, 14(7), 8693-8710.
24. Kumar, R., Prakash, K., Mann, V. S., Rao, A. U., Pattanaik, A., Ojha, M. K., ... & Abate, L. (2025). Sustainable Micromachining of Additively Manufactured Nickel Alloy: Effect of Biodegradable MQL on Tool Wear and Surface Quality. Journal of Engineering, 2025(1), 7252262.
25. Katam, A. K., Mohanty, R. C., & Kolakoti, A. (2023). The role of bio-based cutting fluids for sustainable manufacturing and machining processes: A holistic review. Mechanical Engineering for Society and Industry, 3(3), 166-180.
26. Panda, D., Kumari, K., & Dalai, N. (2022). Performance of Minimum Quantity Lubrication (MQL) and its effect on Dry Machining with the addition of Nano-particle with the biodegradable base fluids: A review. Materials Today: Proceedings, 56, 1298-1301.
27. Makhesana, M. A., Patel, K. M., Ghetiya, N. D., Binali, R., & Kuntoğlu, M. (2024). Evaluation of drilling and hole quality characteristics in green machining aluminium alloys: A new approach towards green machining. Journal of Manufacturing Processes, 129, 176-186.
28. Singh, T., Singh, C. D., & Singh, R. (2023). A review on minimum quantity lubrication (MQL) assisted machining processes using mono and hybrid nanofluids. Industrial Lubrication and Tribology, 75(9), 1054-1076.
29. Mishra, N. K., Kashyap, D. P., & Singh, R. (2026). Minimum Quantity Lubrication (MQL) for Sustainable and High-Performance Machining: A Comprehensive Review. Smart Sustainable Materials Advancing Remanufacturing and Technology: Sustainable Technology for Product Design, Manufacturing, and Remanufacturing: An Emerging Road Map from Industry 4.0 to 6.0 (Volume II), 113-125.
30. Ghuge, N. C., & Palande, D. D. (2022). The emergence of MQL with vegetable oil as a green manufacturing technique: a review. SAMRIDDHI: A Journal of Physical Sciences, Engineering and Technology, 14(01), 66-71.