ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24MAR1980

Enhancing Polybutylene Terephthalate (PBT) Composites: A PROMETHEE-Based Comparative Study of Reinforcement Materials

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Abstract:- Polybutylene terephthalate (PBT) composites hold significant potential across various industrial applications due to their desirable mechanical, thermal, and electrical properties. In this study, we utilized the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) method to evaluate six alternative reinforcement materials for PBT composites: Glass Fibers (GF), Carbon Fibers (CF), Natural Fibers (NF), Carbon Nanotubes (CN), Nano-clay Particles (NP), and Aramid Fibers (AF). The evaluation parameters considered were Tensile Strength (MPa), Flexural Strength (MPa), Thermal Conductivity (W/mK), Electrical Conductivity (S/m), and Cost ($). Through comprehensive analysis, Carbon Nanotubes emerged as the top-ranked reinforcement material, exhibiting exceptional performance across all evaluation parameters. With high Tensile Strength, Flexural Strength, and Thermal Conductivity, combined with significant Electrical Conductivity, Carbon Nanotubes demonstrated their suitability for demanding applications. Additionally, while the Cost factor was comparatively higher, its superior performance justifies the investment. Conversely, Natural Fibers received the lowest rank among the alternatives. Despite potential advantages in cost-effectiveness and environmental sustainability, Natural Fibers exhibited inferior mechanical and thermal properties compared to other materials. Their low Tensile Strength, Flexural Strength, and negligible Electrical Conductivity highlight limitations in performance for many industrial applications. This study provides valuable insights for engineers and material scientists in selecting suitable reinforcement materials for PBT composites based on specific performance criteria. The PROMETHEE method offers a systematic approach to decision-making, facilitating informed choices in material selection for diverse applications. Future research could explore optimization strategies and further investigate the properties and potential applications of emerging reinforcement materials for PBT composites.

Keywords:- *Polybutylene Terephthalate (PBT); Preference Ranking Organization Method for Enrichment Evaluations(PROMETHEE); Glass Fibers (GF) ; Carbon Fibers (CF) ; Natural Fibers (NF) ; Carbon Nanotubes (CN).*

I. INTRODUCTION

Poly (butylene terephthalate) (PBT) stands out as a crucial semi-crystalline engineering thermoplastic renowned for its manifold advantageous properties, encompassing rapid crystallization, commendable solvent resistance, thermal stability, and superb processing characteristics. As a result, it holds broad applicability in various sectors including automotive, electrical, packaging, and consumer goods. Despite its inherent advantages, PBT frequently undergoes modifications by blending with other polymers and integrating particulate fillers to augment its characteristics. Notably, PBT/glass fiber composites have garnered considerable attention among researchers for reinforcement. However, the incorporation of glass fibers often poses challenges such as diminished flowability, injection molding delays, and the necessity for high injection pressures, leading to surface finish degradation due to warping or distortion in molded articles. Other fillers employed to reinforce PBT include oxidized single-wall carbon nanotubes, glass beads, montmorillonite, and SiO2. However, there is a paucity of scientific literature regarding the utilization of mineral fillers in polyester-based composites. Several studies have explored carbon fiber-reinforced PBT composites, including investigations by Ng et al. and Wiedmer et al. Ng et al. examined the impact of combining boron nitride (BN) and carbon fiber (CF) within the PBT matrix, revealing reduced electrical conductivity in the resulting composites. However, thermal conductivity showed no improvement compared to PBT/BN composites. Wiedmer and colleagues conducted an investigation into the impacts of electron beam radiation on carbon fiber-reinforced composites of polybutylene terephthalate (PBT), polyphenylene sulfide (PPS), and polyamide (PA), discerning minimal alterations in properties post-irradiation. Furthermore, Chen and colleagues conducted a study examining polybutylene terephthalate (PBT) matrix composites reinforced with recycled carbon fibers (RCF), with a specific emphasis on enhancing the interfacial adhesion between RCF and the PBT matrix through surface treatment. Their findings demonstrated that the surface-treated RCF significantly enhanced the mechanical properties, heat distortion temperature, and thermal stability of the composites. Examination of fracture surface morphologies highlighted a uniform distribution of reinforced carbon fibers (RCF) within the polybutylene terephthalate (PBT) matrix. This study aimed to investigate the influence of fiber length and dispersion on the rheological, dynamic mechanical, thermal, and mechanical properties of long glass fiber (LGF)/PBT composites. The goal was to develop novel LGF-reinforced granulating composites with varying original glass fiber lengths that align with those of PBT matrix resins. However, pure PBT's applications are constrained by its inadequate impact strength and heat distortion temperature. While considerable research has focused on blending polybutylene terephthalate (PBT), there is a noticeable scarcity of scientific literature concerning polyester-based composites. Among reinforcement methods, PBT/glass fiber composites have received significant attention from researchers. Additionally, other fillers like oxidized single-wall carbon nanotubes, montmorillonite, and SiO2 have been explored for reinforcing PBT. In the engineering polymer industries, PBT serves as a widely utilized matrix polymer in the production of fiber-reinforced composites. Its popularity stems from its advantageous characteristics, including commendable mechanical properties, chemical resistance, moldability, and rapid crystallization rate. Numerous researchers have extensively examined glass fiber (GF) reinforced polybutylene terephthalate (PBT) composites, focusing on diverse aspects including mechanical properties, crystallization kinetics, thermal characteristics, and the performance of rubber-toughened PBT/GF blends. These investigations have led to the substitution of metal components with GF-reinforced polymer composites due to their reasonable cost and lightweight attributes. PBT, a semi-crystalline thermoplastic, finds widespread use in engineering applications owing to its advantageous blend of mechanical and chemical properties, coupled with ease of processing. Nonetheless, PBT does come with drawbacks such as its low notch impact strength and a relatively modest heat deflection temperature. To address the growing need for improved material performance, adaptations of PBT include blending it with other polymers and integrating reinforcements. In scientific literature, there's a dearth of information concerning the utilization of mineral fillers in polyester-based composites, including Poly (butylene terephthalate) (PBT), despite the widespread use of diverse reinforcements like glass fibers and carbon fibers. PBT, belonging to the polyester family, is a semi-crystalline polymer renowned for its versatile mechanical and thermal characteristics, as well as its swift crystallization rates, making it a preferred choice in engineering applications. Mineral fillers are often integrated into commercial PBT grades to bolster mechanical attributes, stabilize dimensions, and mitigate the coefficient of thermal expansion. Common mineral fillers utilized in polybutylene terephthalate (PBT) include clay, talc, silica, mica, wollastonite, barite, and milled glass. Contemporary studies have investigated the isothermal and non-isothermal crystallization behaviors of PBT, its blends, and composite materials. Nonetheless, the focus of non-isothermal investigations on PBT composites primarily centers on nanocomposites. Mulla and colleagues investigated the non-isothermal crystallization kinetics of PBT/nanoclay and PBT/nanocarbon fiber composites using various macro kinetic models. They observed that even with minimal amounts of carbon nanofiber and nanoclay (2 wt.%), the activation energy for crystallization decreased, leading to enhanced crystallization rates. However, higher filler concentrations resulted in diminished crystallization rates. Zhang et al. examined the non-isothermal crystallization of PBT nucleated with elastomer-modified nano-SiO2, a commercial nucleating agent (P250), and talc. They found that these additives reduced crystallization time by altering the nucleation mechanism and crystal growth in PBT.

II. MATERIALS & METHOD

A. Materials

The alternatives for reinforcement materials in polymer composites include glass fibers, carbon fibers, natural fibers, carbon nanotubes, nano-clay particles, and aramid fibers. Glass fibers offer conventional strength, while carbon fibers provide exceptional mechanical properties. Natural fibers are renewable but typically offer lower performance. Carbon nanotubes and nano-clay particles offer advanced properties, and aramid fibers provide high tensile strength and abrasion resistance. The evaluation parameters provide comprehensive insights into the performance and characteristics of different reinforcement materials for polymer composites. Tensile Strength (MPa) measures the maximum stress a material can withstand under tension, indicating its structural integrity. Flexural Strength (MPa) assesses a material's resistance to bending or deformation, crucial for load-bearing applications. Thermal Conductivity (W/mK) quantifies a material's ability to conduct heat, influencing its thermal stability and insulation properties. Electrical Conductivity (S/m) indicates the material's ability to conduct electricity, vital for electrical applications. Cost ($) represents the economic feasibility of using each material, considering production expenses and market affordability. These parameters collectively aid in selecting the most suitable reinforcement material based on specific performance requirements and budget constraints.

B. Method

PROMETHEE, developed by Brans and Vincke in 1985 and further refined by Brans et al., offers a straightforward approach to multi-criteria analysis compared to other available techniques. It falls under partial aggregation methods, contrasting with complete aggregation methods like MAUT. PROMETHEE excels in ranking numerous and intricate criteria within a finite set of alternatives. It primarily relies on two key pieces of information: the relative weights of criteria and decision-makers' preferences. Brans categorizes PROMETHEE as an outranking method, aiming to enhance the dominance relation, thereby facilitating comparisons among actions. Roy classifies PROMETHEE as a type II multicriteria aggregation procedure. The method comprises two phases: establishing an outranking relation and leveraging it for decision support. Ulengin et al. highlight PROMETHEE's user-friendly nature, its successful application in real-world planning, and its ability to provide complete rankings. PROMETHEE I and PROMETHEE II, developed by Brans et al., enable partial and complete rankings, respectively. These methods are straightforward compared to other multi-criteria analysis techniques and are particularly suited for scenarios involving a finite number of alternatives evaluated against multiple, sometimes conflicting criteria. The evaluation table serves as the starting point for implementing PROMETHEE, where alternatives are assessed across various criteria, requiring two additional types of information for execution.

The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) method stands out among classical approaches for Multi-Attribute Decision Making (MADM) due to its outranking-based framework, facilitating decision-makers in complex scenarios. Particularly beneficial in real-world contexts where human judgment is crucial, PROMETHEE accommodates collaboration limitations among specialists. By comparing alternatives pairwise, PROMETHEE mitigates round-off errors inherent in direct ranking, offering flexibility in criterion selection and avoiding data normalization challenges. Notably, researchers have extended PROMETHEE's applicability, exploring areas like mobile application ranking, material selection, and supplier procurement using fuzzy and intuitionistic fuzzy sets. Building on these advancements, we enhance PROMETHEE by leveraging Intuitionistic Fuzzy Sets (IFSSs), introducing six preference relations and three preference structures. Our novel approach, rooted in IFSSs, adeptly addresses uncertainty and neutrality, common in real-world decision-making, amplifying PROMETHEE's utility in diverse scenarios.

Table 1 presents a comparative analysis of different reinforcement materials for polybutylene terephthalate (PBT) composites using the PROMETHEE method. The table includes key mechanical and physical properties such as tensile strength, flexural strength, thermal conductivity, electrical conductivity, and cost. Among the materials assessed, carbon fibers exhibit the highest tensile strength (300 MPa) and flexural strength (250 MPa), while also boasting the highest thermal conductivity (500 W/mK) and electrical conductivity (1.00E+06 S/m). Conversely, natural fibers demonstrate the lowest mechanical properties but offer a more affordable option with the lowest cost ($3). The analysis highlights trade-offs between performance and cost across different reinforcement materials, providing valuable insights for material selection in composite fabrication.

Figure 1 presents the evaluation of different reinforcement materials using the PROMETHEE method. Carbon fibers exhibit the highest tensile and flexural strengths, while carbon nanotubes demonstrate superior thermal and electrical conductivities. However, glass fibers offer a more balanced performance across parameters at a relatively lower cost compared to other materials.

Table 2 presents normalized data using the PROMETHEE method for evaluating different reinforcement materials for polymer composites. The values represent the relative performance of each material across various parameters. Carbon fibers emerge as the top performer, scoring 1 across all criteria, showcasing superior tensile and flexural strength, high thermal conductivity, excellent electrical conductivity, and reasonable cost. Carbon nanotubes follow closely, excelling in tensile and flexural strength, thermal conductivity, and electrical conductivity. Glass fibers exhibit moderate performance, particularly in strength-related metrics. Aramid fibers show competitive tensile and flexural strength but lack in other areas. Natural fibers and nano-clay particles display lower performance overall, particularly in mechanical and thermal properties.

Table 3 presents pairwise comparisons using the PROMETHEE method for different evaluation parameters of the composite materials. Each cell represents the preference degree (D) between two materials concerning a specific parameter. Positive values indicate preference towards the row material over the column material, while negative values indicate preference towards the column material over the row material. The parameters include Tensile Strength, Flexural Strength, Thermal Conductivity, Electrical Conductivity, and Cost. Positive D values signify better performance of row materials, while negative values suggest better performance of column materials. These comparisons aid in determining the most suitable reinforcement material for polybutylene terephthalate (PBT) composites based on various criteria.

Table 4 presents preference values calculated using the PROMETHEE method for various criteria including tensile strength, flexural strength, thermal conductivity, electrical conductivity, and cost. The values range from 0 to indicate no preference to higher values indicating stronger preference. These values guide decision-making by highlighting material preferences based on specified criteria.

Table 5 presents the results of the PROMETHEE method, indicating the pairwise comparison between criteria (C1-C6) and the aggregated positive and negative values. Positive values denote the preference for the row criterion over the column criterion, while negative values suggest the opposite. The highest positive values signify the most preferred criteria, while negative values indicate inferior options.

Table 6 presents the results of the PROMETHEE method for evaluating different reinforcement materials. The "Net flow" column quantifies the overall desirability of each material, with higher values indicating greater suitability. Based on this analysis, Carbon Nanotubes demonstrate the highest net flow, ranking first, while Natural Fibers exhibit the lowest net flow, ranking sixth.

Figure 1 presents the evaluation of different reinforcement materials using the PROMETHEE method. Carbon fibers exhibit the highest tensile and flexural strengths, while carbon nanotubes demonstrate superior thermal and electrical conductivities. However, glass fibers offer a more balanced performance across parameters at a relatively lower cost compared to other materials.

Figure 2 presents the positive and negative flows calculated using the PROMETHEE method for different reinforcement materials in PBT composites. Positive flow values indicate the superiority of a material in certain criteria, while negative flows denote inferiority. For instance, Carbon Fibers exhibit significantly high positive flows, suggesting their superiority across evaluated parameters. Conversely,

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24MAR1980

Natural Fibers demonstrate negligible positive flows, indicating limited advantages over other materials.

The figure 3 presents the results of applying the PROMETHEE method to assess the net flow and rank of various reinforcement materials for polymer composites. Carbon nanotubes exhibit the highest net flow, ranking first, indicating their superior overall performance. Natural fibers rank lowest, suggesting limited effectiveness compared to other materials.

Table 1. Polybutylene Terephthalate Composites

Reinforcement Material	Tensile Strength (MPa)	Flexural Strength (MPa)	Thermal Conductivity (W/mK)	Electrical Conductivity (S/m)	Cost ($)
Glass Fibers	150	180	0.25	1e-12	5
Carbon Fibers	300	250	500	1e6	20
Natural Fibers	80	100	0.15	1e-14	3
Carbon Nanotubes	250	220	1000	1e5	50
Nano-clay Particles	120	150	0.10	1e-15	10
Aramid Fibers	200	180	030	1e-13	30
Max	300	250	1000	1000000	50
Min	80	100	0.1	1E-15	3
max-Min	220	150	999.9	1000000	47

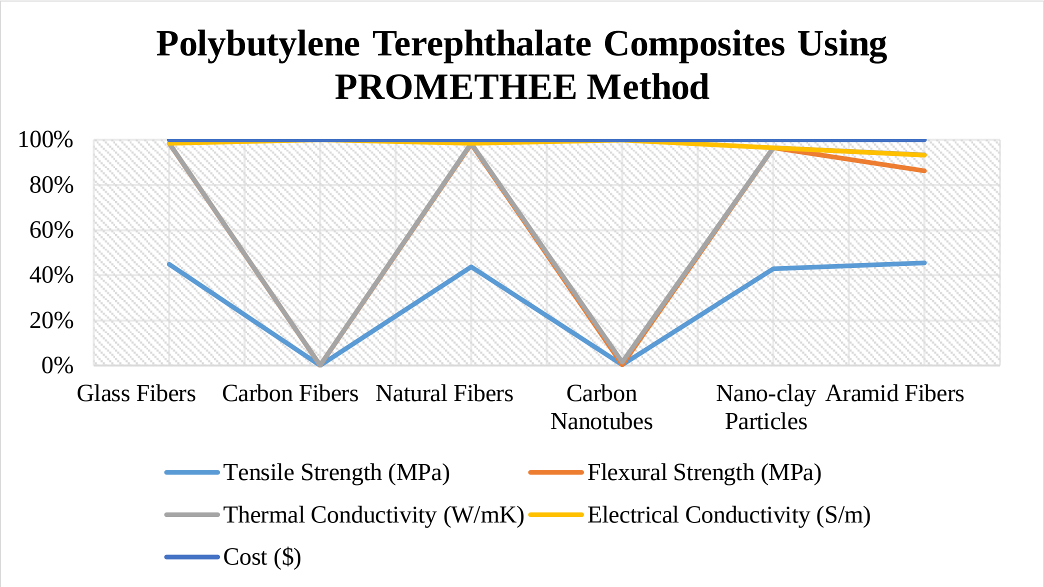

Fig 1. Polybutylene Terephthalate Composites

Table 2. Normalized Matrix

Normalized Matrix					
Glass Fibers	0.31818	0.5333	0.0002	9.99E-19	0.0426
Carbon Fibers	1	1	0.4999	1	0.3617
Natural Fibers	0	0	5E-05	9E-21	0
Carbon Nanotubes	0.77273	0.8	1	0.1	1
Nano-clay Particles	0.18182	0.3333	0	0	0.1489
Aramid Fibers	0.54545	0.5333	0.0299	9.9E-20	0.5745

Table 3. Pair Wise Comparison

	Pair Wise Comparison				
D 1,2	-0.6818	-0.4667	-0.5	-1	-0.319
D 1,3	0.31818	0.5333	0.0001	9.9E-19	0.0426
D 1,4	-0.4545	-0.2667	-1	-0.1	-0.957
D 1,5	0.13636	0.2	0.0002	9.99E-19	-0.106
D 1,6	-0.2273	0	-0.03	9E-19	-0.532
D 2,1	0.68182	0.4667	0.4998	1	0.3191
D 2,3	1	1	0.4999	1	0.3617

ISSN No:-2456-2165
https://doi.org/10.38124/ijisrt/IJISRT24MAR1980

D 2,4	0.22727	0.2	-0.5	0.9	-0.638
D 2,5	0.81818	0.6667	0.4999	1	0.2128
D 2,6	0.45455	0.4667	0.47	1	-0.213
D 3,1	-0.3182	-0.5333	-1E-04	-9.9E-19	-0.043
D 3,2	-1	-1	-0.5	-1	-0.362
D 3,4	-0.7727	-0.8	-1	-0.1	-1
D 3,5	-0.1818	-0.3333	5E-05	9E-21	-0.149
D 3,6	-0.5455	-0.5333	-0.03	-9E-20	-0.574
D 4,1	0.45455	0.2667	0.9998	0.1	0.9574
D 4,2	-0.2273	-0.2	0.5001	-0.9	0.6383
D 4,3	0.77273	0.8	0.9999	0.1	1
D 4,5	0.59091	0.4667	1	0.1	0.8511
D 4,6	0.22727	0.2667	0.9701	0.1	0.4255
D 5,1	-0.1364	-0.2	-2E-04	-1E-18	0.1064
D 5,2	-0.8182	-0.6667	-0.5	-1	-0.213
D 5,3	0.18182	0.3333	-5E-05	-9E-21	0.1489
D 5,4	-0.5909	-0.4667	-1	-0.1	-0.851
D 5,6	-0.3636	-0.2	-0.03	-9.9E-20	-0.426
D 6,1	0.22727	0	0.0298	-9E-19	0.5319
D 6,2	-0.4545	-0.4667	-0.47	-1	0.2128
D 6,3	0.54545	0.5333	0.0299	9E-20	0.5745
D 6,4	-0.2273	-0.2667	-0.97	-0.1	-0.426
D 6,5	0.36364	0.2	0.0299	9.9E-20	0.4255

Table 4. Preference Value

	Preference Value					
	0.2336	0.165	0.3355	0.102	0.042	
D 1,2	0	0	0	0	0	0
D 1,3	0.0743	0.088	3E-05	1E-19	0.002	0.164
D 1,4	0	0	0	0	0	0
D 1,5	0.0319	0.033	5E-05	1E-19	0	0.065
D 1,6	0	0	0	9E-20	0	9E-20
D 2,1	0.1593	0.077	0.1677	0.102	0.014	0.52
D 2,3	0.2336	0.165	0.1677	0.102	0.015	0.684
D 2,4	0.0531	0.033	0	0.092	0	0.178
D 2,5	0.1911	0.11	0.1677	0.102	0.009	0.58
D 2,6	0.1062	0.077	0.1577	0.102	0	0.443
D 3,1	0	0	0	0	0	0
D 3,2	0	0	0	0	0	0
D 3,4	0	0	0	0	0	0
D 3,5	0	0	2E-05	9E-22	0	2E-05
D 3,6	0	0	0	0	0	0
D 4,1	0.1062	0.044	0.3354	0.01	0.041	0.536
D 4,2	0	0	0.1678	0	0.027	0.195
D 4,3	0.1805	0.132	0.3355	0.01	0.042	0.701
D 4,5	0.138	0.077	0.3355	0.01	0.036	0.597
D 4,6	0.0531	0.044	0.3255	0.01	0.018	0.451
D 5,1	0	0	0	0	0.005	0.005
D 5,2	0	0	0	0	0	0
D 5,3	0.0425	0.055	0	0	0.006	0.104
D 5,4	0	0	0	0	0	0
D 5,6	0	0	0	0	0	0
D 6,1	0.0531	0	0.01	0	0.023	0.086
D 6,2	0	0	0	0	0.009	0.009
D 6,3	0.1274	0.088	0.01	9E-21	0.024	0.25
D 6,4	0	0	0	0	0	0
D 6,5	0.0849	0.033	0.01	1E-20	0.018	0.146

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24MAR1980

Table 5. Positive Negative value

	C1	C2	C3	C4	C5	C6
C1	0	0.5197	0	0.536491	0.0045	0.0856
C2	0	0	0	0.194831	0	0.009
C3	0.16427	0.684	0	0.700762	0.1039	0.2499
C4	0	0.178	0	0	0	0
C5	0.06494	0.5801	2E-05	0.596925	0	0.1461
C6	9.2E-20	0.4431	0	0.450864	0	0
Positive	0.22922	2.4048	2E-05	2.479873	0.1084	0.4906
Negative	0.0382	0.4008	3E-06	0.413312	0.0181	0.0818

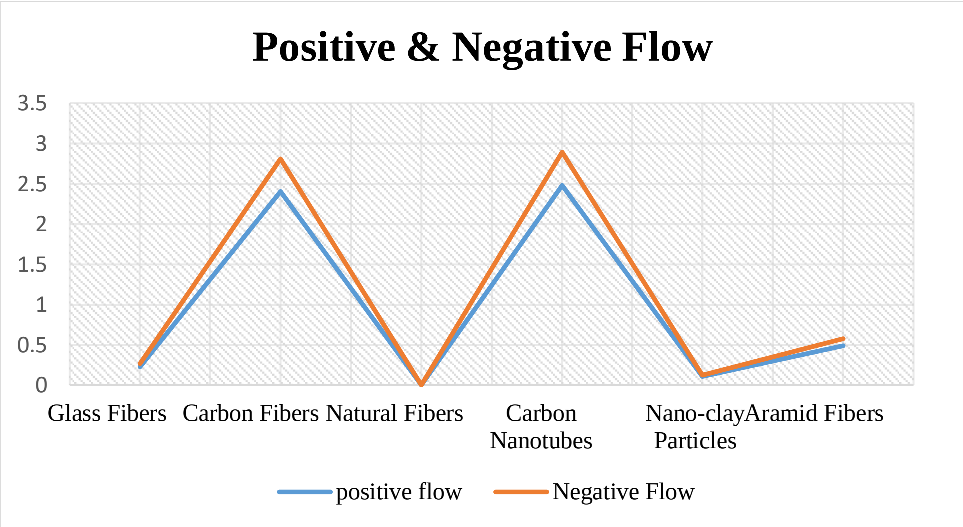

Fig 2. Positive and Negative flow

Table 6. Net Flow & Rank

	Net flow	Rank
Glass Fibers	0.191013853	4
Carbon Fibers	2.004037852	2
Natural Fibers	1.39806E-05	6
Carbon Nanotubes	2.066560527	1
Nano-clay Particles	0.090304105	5
Aramid Fibers	0.408838278	3

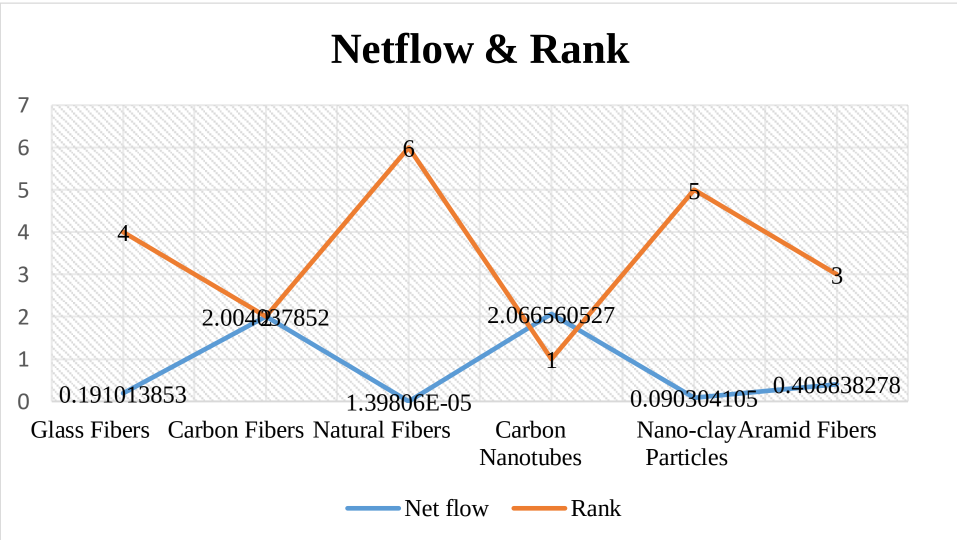

Fig 3. Net flow and Rank

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24MAR1980

III. CONCLUSION

For this investigation, we utilized the PROMETHEE method to assess a range of reinforcement materials intended for polybutylene terephthalate (PBT) composites. The alternatives considered were Glass Fibers, Carbon Fibers, Natural Fibers, Carbon Nanotubes, Nano-clay Particles, and Aramid Fibers. The evaluation parameters included Tensile Strength (MPa), Flexural Strength (MPa), Thermal Conductivity (W/mK), Electrical Conductivity (S/m), and Cost ($). Through comprehensive analysis, we have derived insightful conclusions regarding the suitability of these reinforcement materials for enhancing the properties of PBT composites. Carbon Nanotubes emerged as the top-ranking material based on the PROMETHEE method. This result is attributed to their exceptional mechanical, thermal, and electrical properties, as well as their relatively high cost. Carbon Nanotubes demonstrated superior tensile and flexural strengths in comparison to other available alternatives, indicating their potential for imparting outstanding mechanical reinforcement to PBT composites. Additionally, their high Thermal Conductivity and Electrical Conductivity suggest suitability for applications requiring thermal or electrical conductivity. However, their elevated cost may pose challenges for widespread adoption, particularly in cost-sensitive applications. Following Carbon Nanotubes, Carbon Fibers secured the second rank in our evaluation. Carbon Fibers demonstrated excellent mechanical properties, comparable to Carbon Nanotubes, making them suitable for high-performance applications where strength and stiffness are paramount. Although Carbon Fibers exhibit relatively high Thermal Conductivity and Electrical Conductivity, their cost-effectiveness compared to Carbon Nanotubes enhances their attractiveness for certain applications. Glass Fibers attained the third rank in our assessment, offering good mechanical properties at a relatively lower cost compared to carbon-based materials. Glass Fibers are widely used in composite applications due to their favorable balance of properties and cost-effectiveness. However, their comparatively lower mechanical performance and thermal properties limit their suitability for high-end applications requiring superior performance. Aramid Fibers ranked fourth in our evaluation, showcasing commendable mechanical properties, particularly in terms of impact resistance and toughness. Aramid Fibers are known for their exceptional strength-to-weight ratio and resistance to abrasion, making them suitable for applications requiring durability and impact resistance. Nano-clay Particles secured the fifth rank, exhibiting modest improvements in mechanical properties and thermal stability. Nano-clay Particles offer enhancements in barrier properties and flame retardancy, making them attractive for applications requiring improved safety and environmental performance. Natural Fibers obtained the lowest rank in our assessment due to their relatively lower mechanical properties compared to synthetic fibers. Although Natural Fibers offer environmental advantages and cost-effectiveness, their limited mechanical performance constrains their application range to less demanding applications where sustainability is prioritized over performance. The PROMETHEE method facilitated a systematic evaluation of reinforcement materials for PBT composites, providing valuable insights into their strengths, weaknesses, and suitability for various applications. The results of this study can guide material selection decisions and inform the development of PBT composites tailored to specific performance requirements and cost considerations.

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