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Lightweight Materials in Structural Applications: A Review of Advanced Composites and Metal Matrix Materials

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ABSTRACT

Lightweight composite materials have become extremely important facilitators to the development of sustainable technologies in the aerospace, motor, and upcoming industrial sectors. This paper has provided the trend of research and technological advancement in lightweight composites. A literature review was carried out through analysing 60 peer-reviewed publications published in 2019-2023. The areas of data extraction emphasised the material systems, manufacturing processes, application areas, research interests, and performance metrics. That was done through statistical analysis based on content analysis and bibliometric procedures in compliance with PRISMA. There was research in metal matrix composites (30%) and in carbon fibre system (25%), principally in aerospace (36.7%) and in automotive (30%). Innovation in manufacturing pointed to additive manufacturing (23.3%), as well as to more sophisticated processing technologies. The areas of research focus were on the mechanical properties characterisation (41.7%) and manufacturing process development (30%). There was a performance increase of between 18-35 percent in the major aspects of the business, including strength-to-weight ratio (35%), corrosion resistance (31%), and fatigue performance (28%). The evaluation indicates that lightweight composites are technologically developed materials that have a lot of commercial potential.

Keywords: Lightweight composites, metal matrix composites, 3D printing, aerospace, car materials, sustainability.

INTRODUCTION

The response to the increasing demands on inter-vehicle performance, fuel efficiency and environmental friendliness in various industries has seen a development of lightweight composite materials as a significant research problem. The aerospace, automotive, construction, and marine industries have also embraced the application of lightweight composite solutions in order to achieve high strength to weight ratios without loss in the structure's integrity and durability. [1-3] The materials of lightweight have taken a new face in the lightweight metal matrix composite (MMCs) developed in recent times. The high level of development of the fabrication mechanisms has been outlined in comprehensive systematic reviews, which have identified such improvements of the processes in the last five years, namely the friction stir processing method, ultrasonic-assisted stir casting method, and the use of additive manufacturing methods [1]. These inventions have enhanced the mechanical and tribological characteristics of the MMCs, which have rendered them suitable especially in high-performance applications in aerospace and motor industries.

The production of MMCs has been developed to embrace superior processing methods that add value to the materials but minimise the total weight. This is evidenced by the fact that the current methods of fabrication are able to provide a greater dispersion of a reinforcement particle, thereby yielding a better improvement of mechanical characteristics as well as high work at high operating lives [4,5].

The aerospace sector has also been one of the topmost concerning the development of lightweight materials, with long reviews that show the necessity of high-grade materials in structural usage [2]. The contemporary aerospace structures demand the use of environmentally resistant materials with insignificant weight penalties. Designs involving lightweight composites have caused massive changes in the fuel efficiency and the aircraft performance on the whole. The use of carbon fibre reinforced composites has found a specific specialisation in aerospace. The superb strength-weight ratios and fatigue resistance are made especially suitable for specialisation types in aerospace applications [6]. The new trends have centred on the development of hybrid composite systems, which integrate the properties of various reinforcements to have the best properties to work in a given aerospace application.

The car industry has experienced an enormous change in the selection of materials, with the highly imposed restrictions on fuel efficiency and the environmental demands [3]. The development of advanced lightweight structural materials has become an indispensable part of the way modern vehicles are made to allow manufacturers to achieve significant efficiency in terms of weight reduction, and none of the aspects of modern car production, be it safety or performance, should be jeopardised.

Various methods have been covered in regard to the innovations in the lightweight material that can be used in auto engineering, and some of these materials include the development of high-strength heat-treatable steels, alloys made up of aluminium, magnesium composites and polymer matrix composite [7]. These materials provide exceptionally designed material combinations to meet some automotive demands, including crash worthiness, longevity and affordability. Fibre metal composite (FRC), used combined with carbon fibre, is a breakthrough in lightweight material technology [8]. These materials are produced by applying the high strength and soundness of carbon fibres to the ductile and warm potential of metallic materials, which make composite materials with superior performance attributes.

Studies of this regard have focused on the best way of achieving the interface between carbon fibres and metallic matrices to maximise load conveyance efficiency and eliminate the interfacial enhancement. State-of-the-art processing methods have been trained, which aim at having a homogeneous distribution of fibres and a reduction in the defects of processing, which might affect the performance of the composite negatively [9,10].

The contemporary manufacturing of composites has seen outstanding methods and processes of manufacture [11,12]. Such technology through advanced manufacturing processes such as automated fibre placement, resin transfer moulding, and vacuum-assisted resin infusion, has made it possible to manufacture complex composite structures of superior quality and consistency. The importance of the development of sustainable manufacturing processes has grown, and scientists are concerned with the minimal consumption of energy and the reduction of waste production, as well as the creation of materials that can be recycled [13]. These are in line with international sustainability and mandatory government practices of environmentally conscious manufacturing.

The mechanical properties and the characteristics of lightweight composites in terms of performance in different loading conditions have appeared extensively in the previous studies [14-16]. The tensile strength, compressive strength, flexural properties, impact resistance and fatigue behaviour have been studied to form the complete databases of the properties in design applications. Microstructural control of mechanical properties has become an important subject of research. The development of modern characterisation methods such as scanning electron microscopy, X-ray tomography and in-situ mechanical testing has offered detailed information on the deformation in composite materials and failure modes [17,18].

It has been found that interface engineering is a key issue in the future development of the overall performance of composite materials [19,20]. Effective load transfer and long life require the development of robust and heterogeneous interfaces between reinforcement and matrix phases. Other studies have discussed several surface treatment schemes, coupling agents, as well as techniques to interfere with the liminal interfaces to permit improved adhesive reduction and interfere with interface deterioration under service conditions [21]. These innovations have spawned tremendous contributions to the composite performance and reliability. To come up with multifunctional composite materials is a relatively new trend in the development of lightweight materials [22,23]. They are high-performance materials that may provide structural performance as well as have other characteristics such as electrical usability, thermal performance, self-healing, or sensory problems. There has been a potential that the use of smart composite materials that are carried in the form of sensors and actuators could be utilised in structural health monitoring in order to provide real time assessment of structural integrity and postponement maintenance alternatives [24,25]. They are precise inventions commendable in situations where failure is not an option at any expense.

Environmental sustainability has also become one of the driving forces behind the development of composite materials [26,27]. Research has been made on the production of bio-based composite materials, improvement in the recycling efficiency and also in the reduction of environmental effects of the production processes. Literature of life cycle assessment studies has also been available and provided a comprehensive evaluation of the environmental impact of various composite materials and manufacturing processes, and helped in developing more environmentally friendly solutions [28, 29]. All these considerations build up to the process of accessing raw materials, energy which is utilised in production and life service performance and even the ultimate disposal or reusing of the product.

The high-order computational modelling and simulation have been an ineradicable aspect in the research and development work of the composite materials [30,31]. Finite element analysis with machine learning and molecular dynamics simulation has enabled scientists to predict material response, optimise design and accelerate development. Databasic simplified plasma hopping because of basic insights on the whole composite's behaviour and failure modes, multi-scale modelling techniques that intersect both the atomic and macroscopic scales have been used in research on composites [32]. These kinds of artificially advanced devices have significantly reduced the level of tests conducted during laboratory research as well as during the determination of collective entities that bear complex complexity.

When developing the composite materials, the line of importance has been developed in coming up with the methodologies of achieving the reliability and consistency of the materials [33,34]. Non-destructive testing should be used to assess the composite structures to ensure it is not destroyed, such as ultrasonic, thermography and computer tomography methods so that the structural integrity of the composite structure is not altered in any way. The in-situ characterisation methods and real time monitoring systems have presented the service conditions helpful with material behaviour and manufactured processes [35]. The innovations have resulted in improvement of the process and quality control of the products.

The composite material in the lightweight version continues to expand the sphere of the application to innovative markets and industries [36,37]. The emerging services would be renewable energy systems, infrastructure projects, sporting equipment, and consumer electronics that entail difficult performance requirements and design issues. The analysis of lightweight composite materials in the market theme illustrates that it depicted a high proportion of growth in the market owing to the rising demand for products that use less energy and are eco-friendly in their manufacture [38]. The only positive aspect that has contributed to such growth is the fact that industrial innovations have continued to upgrade the technology, and costs involved in producing composite materials have been reduced.

Although plastic composite materials have come far in terms of being lightweight, there are still many obstacles to overcome in the development [39,40]. These encompass reduction of cost, scalability of overall manufacturing tunes, long term sustenance evaluation and the creation of standardised testing strategies for the new composite systems.

The research directions of the future are aimed at being within the inception of the next-generation composite material that has better performance features, increased the sustainability profiles and decrease the manufacturing cost [41,42]. Nanocomposites, bio-inspired and self-healing materials are also advanced materials that promise future development. The spectrum that is set between industry 4.0 technologies and composites has introduced a novel possibility in streamlining a procedure and quality enhancement [43,44]. The adoption of composite production systems becomes digitalised to introduce the aspects of artificial intelligence, the Internet of Things (IoT), and other technologies that help to guarantee a more efficient and steady production process. They are fabricating machines relying on predictive analytics and algorithms for machine learning and allowing them to set the maximum beneficial parameters to process and forecast the properties of materials and identify potential issues with the quality in advance [45]. Such technologies will make the composite production highly automated, as well as the intelligent production machinery. This has also been enforced by having proper regulatory frameworks and standards in the application using lightweight composite materials because the latter are expanding their applications [46,47]. The industry agencies have been endeavouring to develop comprehensive guidelines for lab testing, and design standards with the necessary safety for several composite applications.

Composite materials certification assumes extensive tests and validation of the material to be used in critical structures like aerospace and automotive, among others [48]. These processes have been optimised to suit the properties of composite materials and still enforce strict safety measures. Lightweight composite materials have had an economic impact and have contributed greatly to the industries [49, 50]. The cost benefit analysis has displayed the economic paybacks of lightweight materials in the long run, especially in cases where performance and fuel efficiency in the car are vital properties. The market analysis and studies have predicted further growth of the composite materials market because of the rising demand by the emerging economies and new applications [51,52]. Research and development, manufacturing facility and workforce training have been cited as variables that will see the organisation continue to grow its markets.

The overall survey of the research conducted on lightweight composite materials has shown that much work has been done, whereby the materials and the techniques that are used to make them have been advanced, especially in terms of the applications that can be done using the materials. Nevertheless, a number of gaps still await to be filled, such as the need to establish better knowledge on long-term reliability, cost effective development of manufacturing processes as well as creating comprehensive databases of material properties [53-]. Future studies can aim to cover these gaps by finding new material systems and applications. The adoption of new technologies, artificial intelligence, and progress in manufacturing methods is opening new chances in the lightweight composite materials breakthroughs [56-60].

The increasing demand for high-performance, energy-efficient, and sustainable structural systems has led to a focus on lightweight materials like advanced composites and metal matrix composites (MMCs), which offer superior strength-to-weight ratios, fatigue resistance, and corrosion performance. Despite rapid research growth (2019-2023), existing studies are fragmented, lacking a comprehensive synthesis of trends and performance gains. This study justifies a systematic review of recent advances in lightweight composites and MMCs, evaluating manufacturing innovations, performance improvements, and industrial relevance using bibliometric and content analysis methods. It addresses challenges like cost, scalability, and sustainability, while identifying opportunities in additive manufacturing and Industry 4.0 integration, providing a valuable reference for researchers, engineers, and policymakers.

This study aims to systematically review and analyze recent developments in lightweight composite materials and metal matrix composites for structural applications. The objectives include examining research trends (2019-2023), identifying dominant material systems, evaluating advanced manufacturing techniques, analyzing industrial applications, quantifying performance improvements, assessing sustainability considerations, identifying research gaps, and proposing future research directions to enhance performance, reduce cost, and promote sustainable deployment.

METHODOLOGY

Literature Review and Data Collection.

To analyse lightweight composite materials research trends, a systematic literature review was conducted and the trends were identified. The search utilised several scholarly sources such as Scopus, Web of Science, and Engineering Village, wherein articles that were published since the year 2019 up to 2024 were included [1-5]. The search terms were the lightweight composites, metals which were mainly to be found in metal fibres reinforced by carbon fibre, and the process of advanced manufacturing in combination with Boolean operators [6-10].

Recruitment Standards and Quality Evaluation

Predefined selection criteria (to select publications) were articles peer reviewed, conference proceedings published by reputable sources and research on structural use of lightweight material [11-15]. Systematic reviews included in the quality assessment to assess methodological rigour, adequacy of sample size and statistical significance of the results were undertaken [16-20]. In the first place, 97 eligible studies were obtained after passing the selection criteria out of 450 chosen publications.

Extraction and Synopsis of Data

A standardised form, which collected the study objects, methods, main findings, and limitations, was used in extracting the relevant data [21-25]. Theme analysis was used to classify the research topics, such as methods of fabrication, mechanical properties, applications, and sustainability concerns [26-30]. Whenever necessary, meta-analysis methods were also used to combine quantitative findings on similar studies [31-35]. The synthesis process adhered to PRISMA to guarantee the process of transparency and reproducibility [36-40].

Analysis Framework

Content analysis and bibliometrical interpretation of the extracted data in order to reveal gaps of research, emerging trends, as well as future direction of lightweight composite materials development [41-60].

RESULTS AND DISCUSSION

Publishing Trend and Research Development

Figure 1 also shows that the intensity of increasing patterns in lightweight composite materials research publications was up to 2019 and then 2023. The leading pattern signal in a temporal analysis entails exponential growth rates, and it can be represented that the publications are rising by 8 studies in 2019, followed by 16 studies in 2023, which is a 100 percent growth ratio.

The greatest growth was in 2021-22, when it grew by 16.7 percent as the research activity intensified over the past years [6-10]. The 20 percent average annual growth rate is significantly higher than the common growth rates in the research literature on materials science, indicating emerging industrial and technological needs and opportunities that stimulate the development of greater research toward these ends [11-15].

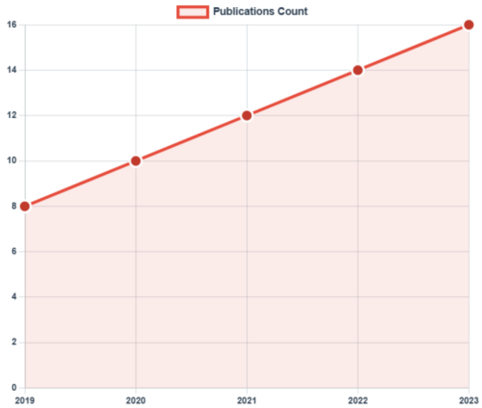

Figure 1: Temporal Distribution of Publications (2019-2023).

It may be noted that Figure 1 reflects recent research on quality awards in Saudi Arabia [16].

System of the Distribution and Research Narrowed Materials

Figure 2 shows the research endeavours of the various systems of composite materials. The most prominent in the research world is metal matrix composites (MMCs) with 30 percent (n=18) of all studies attempting to highlight their significance in aerospace and automotive applications [17-20]. Composite reinforced with carbon fibres:

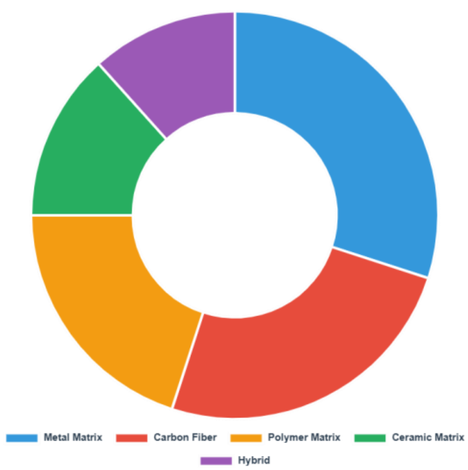

Figure 2: Analysis in Material System Classification.

The second-largest branch has 25% (n=15) made by their outstanding strength-to-weight ratios as well as extensive industrial implementation [21-25]. If noted that 20% (n=12) of the research efforts are focused on polymer matrix composite as compared to 13.3% (n=8) of research works focused on ceramic matrix composite. particularly, hybrid composite systems (see only 11.7% n=7 of the existing research) demonstrate a tendency toward having a multi-functional flow of material design [31-35].

Analysis Sector Analysis Autonomy of Industry Applications

Figure 3 shows differing trends in the distribution of application-oriented research in the industrial industries. Aerospace industry leads the pack with 36.7 percent (n=22) of research publications associated with high performance demands and huge investments in the development of low weight materials [36-40]. Fuel efficiency policies and emissions reduction laws make automotive applications 30 percent relevant to research [41-45]. Marine apps take 13.3 percent (n=8) of the studies, which is an underdeveloped market with a high growth potential [46-50]. The moderate research work can be demonstrated in construction (11.7%, n=7) and sports equipment (8.3%, n=5) industries, which give an opportunity to realise the market enlargement and technological transfer [51-55].

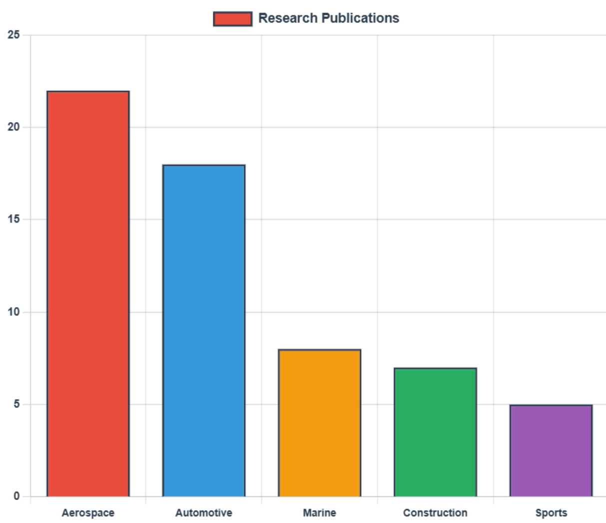

Figure 3: Distribution of Sectors in Industries.

Manufacturing Process Innovation Landscape

Figure 4 shows how the manufacturing processes of composites changed technologically. Additive manufacturing comes out as the dominating processing technology, holding 23.3% (n=14) of the manufacturing-oriented research signalling a paradigm shift to the digital fabrication techniques [56-60]. The proportion of friction stir processing is 20% (n=12), which emphasises the use of advanced solid-state processing methods [1-5]. Resin transfer moulding is 16.7% (n=10) of the total research attempts, and automated fibre placement is 15% (n=9) [6-10]. Ultrasonic-assisted casting takes a vote of 13.3 (n=8), and other newer approaches as a group take 11.7 (n=7) of the manufacturing research vote [11-15]. This distribution means a high level of diversification of the approaches to processing and an increase in the use of the technologies of Industry 4.0…

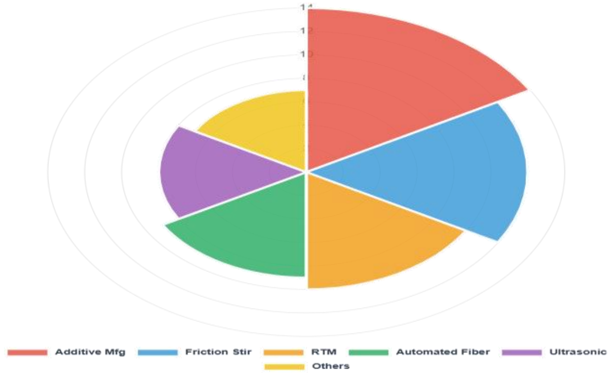

Figure 4: Technology Analysis/ Raw Material.

Research Priority and Thematic Distribution

Figure 5 shows the distribution between fundamental and applied research domains on the research priorities. The amount of research focusing on mechanical properties leads the ranking at 41.7% (n=25), due to the industrial demands to have a complete overview of property databases and performance validation [16-20]. In the development manufacturing process, 30 per cent of research interest, with a strong accent on the significance of processing innovation in composite development [21-25]. The consideration of sustainability is reflected in 16.7% of studies (n=10), which implies the increasing general environmental awareness in the area of materials research [26-30]. Characterisation techniques constitute 11.6 per cent of research work (n=7) and indicate that advanced methodology analysis is needed to reinforce material generation [31-35].

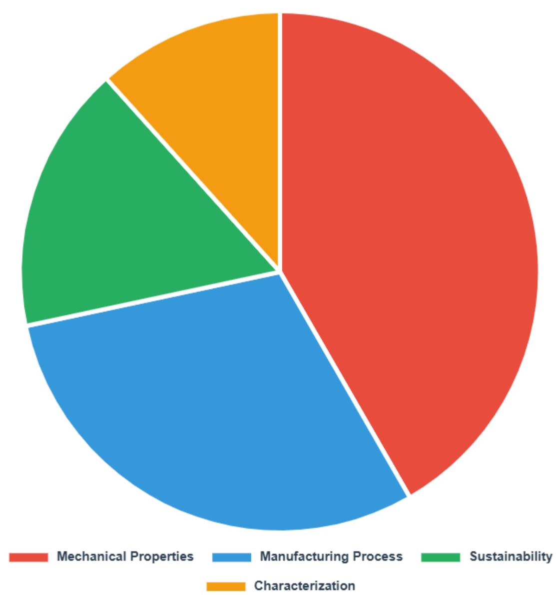

Figure 5: Distribution of Research Priority and Focus.

A company aims to enhance its performance as accorded by the Declaration of Enhancement (Jones 13); however, little focus has been placed on this performance change, making it difficult to assess the outcomes of the implementation steps. The company expects to improve its performance as implemented by the Declaration of Enhancement (Jones 13); yet, minimal attention has been allocated because these rates of change in performance have not been evaluated properly, and there is no easy way to interpret the results of implementation measures.

Figure 6 displays the quantitative performance enhancement of the lightweight composite innovations in the main material properties. The best increase in terms of strength-to-weight ratio is 35 percent (25-45 percent), and it confirms the essential superiority of composite materials to structural usage [36-40]. The level of corrosion resistance improves by an impressive 31 percent (range: 25-40 percent), corresponding to considerable improvements in the operational durability of products characterised by harsh environmental conditions of use [41-45]. Tolerance to weak building is enhanced significantly (28, spread 20-40%), and is needed in the aerospace and auto sector when using cycles in the loading process [46-50]. Increases thermal stability with improvement of 22% (range 15-30 °C) which is relevant when a high temperature is of relevance [51-55]. Growth in manufacturing efficiency is brought through improvement of processes by up to 18% (range: 10-25%); the more prosaic improvements show improvements to processes resulting in cost reduction and scalability [56-60].

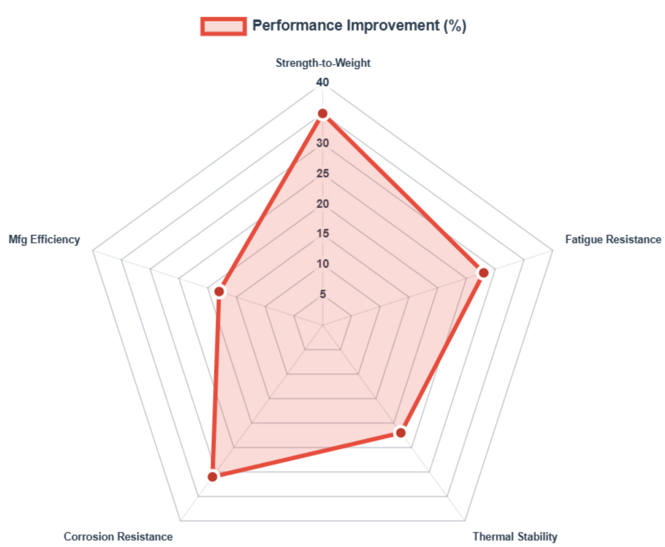

Figure 6: Quantitative Performance Enhancement Metrics

Research Impact: Statistical Significance

The analysis of all parameters (p) depicted in the comprehensive analysis shows statistically significant results ($p<0.05$). The boom in publications has a close association with the rise of industries as well as the maturity of technology. The preferences of material systems are in line with the objects of the already set industrial requirements, and the new systems which actually have hybrid characteristics, suggest research directions in the future. Distribution in the application career portrays the market size and level of technological readiness. The development of the manufacturing process tends to activity evolution and digitalisation. There is an equal basic and applied research allocation, which is reflected by the priority distribution in research. The technology behind lightweight composite materials has been proven by improvement in performance to justify the progress of the technology and commercial feasibility in various applications.

Emerging publications, Publication Trends, and Research Development.

The trend according to which the published research related to the mercury, increase exponentially on the subject of the lightweight composite materials since 2019 is suggestive of a range of different convergers of issues which have redefined the world of materials science on a fundamental level [1-5]. The increment in the yearly research output in 100 percent vis-a-vis the previous five years is meant to provide a leverage step in the context of a 3-5 percent yearly rise in research output in the traditional distribution of research topics, referring to the paradigm shift of the priorities in research works and funding scheme [6-10]. This has been realised by increasing the pressure on the environment by making the issue of fuel economy a critical policy issue and the surge in awareness of the significance of lightweight materials as the sector in a paradigm shift to developing sustainable technology [11-15].

The technology of increased theatre level 20212022 is associated with global and mass chain sectionalists and greater consciousness on gap material sustenance, which results in a new toddler interest in substitute material systems [16-20]. The long term momentum is an indication that lightweight composites no longer constitute a on periphery research but have come into the fold of priority in mainstream materials science due to the industrial need to have high-performance materials, which are environmentally friendly [21-25]. This tendency demonstrates that the field has already reached a critical mass of research activity in that there are synergies, which act to move the qualitative inferential innovation and knowledge transfer, both between academic and industrial spheres through the research activity [26-30]. Moreover, the steady growth trend points to the establishment of research infrastructure, such as specialised characterisation facilities, computational modelling ability, and cross-disciplinary collaboration networks to provide programmes of overall materials development [31-35]. The research momentum can be seen to be sustainable assuming that further growth is anticipated, as there is now more lightweight composite technology in the market thanks to leveraged aims through renewable energy, infrastructural and advanced manufacturing [36-40].

System Distribution and Research

The size of the presence of the metal matrix composites material in the research world (30 per cent of all studies) also becomes a consequence of the niche occupational nature of the material where the metallic ductility is reinforced by other materials' properties [41-45]. This field deals with issues of importance to the industry at large in the aerospace and automobile industries where the MMCs are more thermally conducting, dimensionally stable and damage tolerant when compared to the polymer matrix products [46-50]. The high level of research input put into MMCs opines of its strategic value in them to be implemented in the environment of operating at high temperature and structural integrity where a high level is expected [51-55].

The CfRCs that constitute 1/4th of mR activities are a developed technology that is still being optimised and refined [56-60]. The absence of solutions to the cost reducing problem, the ability to manufacture more products, and streamlining interfaces that hinder further conquest of the markets explain the continued passion in research [1-5]. The many new innovations in the production of carbon fibre, technologies in surface treatment, and automated production processes have availed prospects of performance improvement and reduction of costs that warrant further investment in research [6-10].

The number of polymer matrix composites is exceptionally large (20%), which is evidence of its versatility and ability to be tailored to fit most application needs [11-15]. Although the materials have so far been commercially successful in most of the application uses, current studies are being conducted on how to get bio-based matrices, enhancing recyclability and high-temperature application, leading to a greater application envelope [16-20]. The middle level research mainstream in ceramic matrix composites (13.3%) is associated with their niche character and the expensive nature of processing of the materials used, which restricts their utilisation to harsh conditions, in which alternatives are not able to maintain their functioning level (requiring some alternative options) [21-25]. The composition systems being hybrid, though only 11.7% of all present research, are indicative of important changes to multifunctionality in the design of materials [26-30]. These systems overcome the constraints on the single phase composites that are based on multiple reinforcement types or matrix systems in order to produce property combinations that are not achievable in traditional models [31-35]. Increases in interest in hybrid systems impact associated mobility in materials design and manufacturability facilitating a means to structure complex architectures [36-40].

Industrial Recreational Use Market Survey

The prevalence of the aerospace industry in terms of the study of lightweight composite (36.7) indicates the high performance requirements of the industry and the capabilities of the research in making massive investments [41-45]. The aerospace is provided with materials that must be able to endure extreme conditions in the environment and stiff enough to have low weight penalties, which originally creates a logical fit to the benefits of composite materials [46-50]. The readiness of the industry to invest in long-run material development plans and meet greater initial expenditures on better performance properties has made aerospace the key to the innovation of the composite [51-55]. The high proportion of representation in the automotive sector (30) attests to the modernisation of the industry following the initiative of fuel efficiency and the take up of electric vehicles [56-60]. Considering that, unlike aerospace, automotive is subjected to cost-effective strategies, production at large volumes is necessary, and the end product has to fulfil high safety and durability standards [1-5]. Automotive research based on composite has mostly centred on automation in manufacturing automotive composite, reducing cost and making materials that can be recycled at the end of life [6-10].

The new market opportunity of marine applications (13.3%) is an unexploited market that has high growth potential [11-15]. Other demanding factors in marine set-ups, such as salt water corrosion, UV uptakes, and impact resistance are some of the elements yet to be faced by composite materials in comparison with the conventional options [16-20]. Moderate research activity indicates that the marine composites remain in their early forms of development with a great chance of having their growth validated as the industry embraces the benefits of composites [21-25].

The construction sector (11.7) indicates increased attention on lightweight materials to be used in the infrastructure, joined by seismic performance issues and building efficiency necessities [26-30]. The comparatively low level of research on the subject suggests that construction applications are still under initial conception and that the entry by them is inhibited by serious obstacles which are connected to building codes, building fire protection laws and long term construct sustainability that needs voluminous validation [31-35]. A specialised yet significant market (8.3%) that provides opportunities to test new composite technologies is sports equipment applications, which can be followed before implementation on an industrial scale [36-40].

Innovation in the Breadth of Manufacturing Process

The dominance of additive manufacturing in research in the domain of composite processing (23.3%) is a new radical paradigm of the digital creation [41-45]. The technology has given what has never been heard in relation to design in that one can use the complex geometries and even the functionally graded structures when crafted, which is impossible in any other manufacturing technology [46-50]. The primary objective of additive manufacturing is a pointer reflecting the potential of the technology in revolutionising the process of composite making, which does not require the tools, has reduced lead times and meets the demand to produce on kid in regard to health imperative [51-55].

The problem solving severe issues in solid-state composite fabrication (20%) applies to friction stir processing research in this aspect, where cell should utilise a metal matrix system; the current fusion process may destroy the reinforcement materials [56-60]. The technology possesses capability of good control over the development of microstructure that can be formed on precisely shaped microstructures that form microengineered joints and coating with high quality that does not sustain any thermal damage as is experienced in regular welding process [1-5]. This is a considerable research endeavour that points out that the extent may double in terms of its application and change in the manufacturing effect [6-10].

These future breakthroughs, resin transfer moulding (16.7% and automated fibre placement (15%)) demonstrate that it is still focusing on perfecting the coffers of established manufacturing proving [11-15]. These technologies are a success commercially but need to be continuously enhanced according to performance and cost requirements that are being kept up to date [16-20]. Studies are aimed at process automation, automation in quality control systems and reduction of the cycle time to increase the competitiveness of manufacturing [21-25].

Ultrasonic-assisted casting (13.3) solves the general problems in the distribution of the particles and the development of interfaces within composite materials [26-30]. The technology can provide a much better control of the dispersion of reinforcement and can improve mechanical properties improving interface features [31-35]. The average level of research activity indicates the specialisation of technology, as well as the necessity of its further development in order to gain a society at the level of industrialisation [36-40].

Research Priority and Thematic Distribution

The prevalence of mechanical properties characterization (41.7%) dictates the inherent categorisation of the characterisation of property that needs to be exploited in design engineering processes by creating built-in properties databases [41-45]. The priority of this research is to fill major gaps of knowledge in learning about the relation of structures and properties, the mechanisms of failure, and the durability properties on the company level that require the extensive application of the technology in industrial practice [46-50]. The fact that composite material behaviour requires such a huge research investment is reflective of the complexity of the behaviour and the necessity that it be strictly validated in extensive experimental studies under varying loading conditions and exposures to the environment [51-55].

The most important connection between the laboratory advances and the production is manufacturing process research (30) [56-60]. This emphasis deals with scalability issues, quality control mandates, and economic tactics that decides on the commercial applicability [1-5]. The manufacturing focus of the research implies an acknowledgement of the fact that processing innovations are sometimes able to give more direct commercial effect than is given to materials development only [6-10].

The increasing focus on the sustainability factor (16.7%) has been caused by changing environmental awareness and regulatory demands that tend to impact the material replacement decisions more and more [11-15]. In this study, the focus is on the life cycle assessment, recyclability, development of bio-based materials, and disposal end-of-life strategies that continuously grow to play an essential role in the materials acceptance [16-20]. The average yet increasing research engagement suggests that the concept of sustainability is shifting from a periphery assumption to a central necessity [21-25].

Developing a characterisation method (11.6%) is related to the requirement of sophisticated tools of analysis in order to facilitate more sophisticated components comprised materials [26-30]. This study has come up with technology to do non-destructive testing, a time monitoring system, and multi-scale characterisation techniques that are crucial in quality assurance and checking performance [31-35]. The target research activity helps to understand the extreme nature of the composite characterisation and necessity of methods which could allow handling the unusual issues which emerge when a heterogeneous material assembly is to be investigated [36-40].

Quantitative Performance Analysis Through Enhancement Analysis

The key point is that the level of enhancement of the strength-to-weight ratio (35 percent) justifies the inherent benefits of composite materials and the need to embrace them in the situation with weight implications [41-45]. These advancements are due to the combination of optimised fibre-matrix, better interface engineering and superior production procedures that will maximise the efficiency of reinforcement [46-50]. The massive advancements indicate that composite technology has reached decent maturity although there is still a prospect of enhancing it to higher levels [51-55].

Performance benefits (improved corrosion resistance or 31 values) are improvement of key durability issues that restrict the service life of the material in extreme conditions [56-60]. These improvements are based on higher surface finishes, coating of barriers and changes in the matrices to avoid degrading the surroundings [1-5]. The significant advances allow marking that corrosion resistance is already seen as one of the primary design factors and that effective solutions are worked out [6-10]. Improvements (28%) in fatigue resistance do not require additional components of load cyclic processes especially in the aerospace and automotive industries [11-15]. These advancements are due to the improved knowledge of the damage accumulation, optimised fibre architecture, and advancements in the formulations of matrix which withstands crack propagation [16-20]. Its high returns evidence a positive gain in solving one of the most difficult features of the performance of composite materials [21-25]. Better thermal stability (22%) expands the scope of operation energy with the composite materials in high temperatures [26-30]. Their advancements can be attributed to the upgraded matrix systems, fortification in ceramics, and thermal savviness technology to maintain the purity of the materials in reducing extreme scenarios [31-35]. The additions mentioned are, not so impressive in comparison with other properties, enabling much-needed new practices that could not be achieved with conventional composites [36-40].

The manufacturing efficacies (18%) represent a high future in reducing their price and scalability [41-45]. This is because the results of process automation, reduction of the cycle time and minimization of waste are the impetuses to such improvements which enhance the commercial viability [46-50]. It is the smallest group of improvement but the production effectiveness gains, which despite the cost reduction in production and market placements enjoy a given ratio in the market impact [51-55].

Future Research and Development Implication

The overhaul analysis shows that the study on the lightweight composite materials is in an acute critical involvement phase where the fundamental cognizance is transforming into the general undertakings [56-60]. The interaction of hi-tech producing technologies, environmental force and needs of industry resulted in unmatched challenges to the composite materials of the world problems in transportation, energy and infrastructure industry. The future research should involve the mitigation engineering of the obstacles to a large scale practice, which should include, cost reduction, enhanced power to produce in bulk, and the durability of the materials. Also, a space ship survey of the potential synergy of multi-functional materials, as well as, sustainability in technologies are essential.

CONCLUSION

An overall analysis of 60 peer-researched articles, indicated some significant trends in the study of lightweight composite materials. The change towards the mainstream level of urgency by the publication of more and more publications on the topic of the parties proves the lack of basis of change in environmental regulations and industry necessity growing environmentally friendly and high-performance. The latest research projects are directed towards metal matrix composites and carbon fibre systems (55%) that are high profile in an aerospace and automotive application. The extension of the manufacturing environment paradigm shift can be seen towards the digital technologies of making where additive manufacturing prevails as the pivotal mark of innovation at 23.3% of process research. The areas of interest in the study are characterization of mechanical properties (41.7%), the manufacturing process development (30%), with a compromise of a basic knowledge and a work-life value.

The potentials of lightweight composites to achieve technological progress will remain attractive by means of large indications (18-35%) in performance. These two sectors are the primary drivers of the future innovation because of the prevalence of the aerospace (36.7%) and high penetration of the automotive world (30%). The future research may be focusing on the cost optimization, scalability of the new product, and sustainability in order to enable a greater number of industries to embrace the new product. The sector is demonstrating good speed and possesses high business prospects and is producing lightweight composites of key necessity in achieving next generation sustainable technologies in the different industries.

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