Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering
15 (3) (2023) 0037~0048
DOI 10.71939/jsme.2023.1092090

Research article

Advancing biomedical, food, and industrial applications through carbon nanomaterials: current status and future perspectives

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(Manuscript Received --- 18 Apr. 2023; Revised --- 29 Oct. 2023; Accepted --- 17 Nov. 2023)

Abstract

Carbon nanomaterials, such as carbon nanotubes (CNTs) and graphene, possess remarkable mechanical, electrical, and biological properties, making them promising enhancers in biological materials. Their nanoscale dimensions and large surface area enable targeted interactions with living organisms. However, concerns regarding their cellular compatibility in clinical orthopedic applications persist. To address this, ongoing investigations are examining the interaction of carbon nanomaterials with biological systems, including proteins, nucleic acids, and human cells, to assess their behavior in laboratory and in vivo settings. Studies have demonstrated that composites reinforced with CNTs and graphene enhance the adhesion of osteoblast cells, leading to enhanced bone tissue formation. This potential is expected to drive advancements in reconstructive medicine and bone tissue engineering. Additionally, this article presents current advancements and future research directions in developing CNT and graphene-reinforced implants for bone tissue engineering.

Keywords: CNTs, Graphene, Cellular compatibility, Biomaterials applications, Industry

1- Introduction

Carbon nanomaterials have emerged as promising tools for advancing various applications in the fields of biomedical, food, and industrial sectors. These materials possess unique properties such as high surface area, mechanical strength, and excellent electrical conductivity, making them suitable for a wide range of applications. This article provides an overview of the current status of carbon nanomaterials in these domains, highlighting their significant contributions and potential impact. Furthermore, it discusses future perspectives and potential directions for harnessing the full potential of carbon nanomaterials in advancing biomedical, food, and industrial applications, paving the way for innovative and sustainable technological advancements.

One of the concerns associated with implanting medical devices is the potential impact of ferromagnetic implants containing iron and chromium on resonance imaging. On the other hand, while implants made from CP-Ti exhibit excellent biocompatibility and corrosion resistance, they are vulnerable to degradation and wear which can lead to inflammatory reactions and rejection of metal implants due to the release of metal ions and particle abrasion [1-4]. Such wear and corrosion can also cause chromosomal abnormalities and other negative effects. Ti alloys have become a popular choice for biomedical applications due to their specific strength, corrosion resistance, biocompatibility, and elastic strain. In particular, Ti-6Al-4V alloy has shown promise as a material for tissue engineering scaffolds and load-bearing implants [5-7]. However, in cases where implants do not possess adequate mechanical and biological characteristics, corrective surgeries such as implant removal and replacement may be needed, resulting in additional risks, pain, and expenses for patients [8-11]. In the field of bone tissue engineering, the use of concentrated polymeric materials containing carbon nanotube layers as a substitute for natural bone has been investigated in some cases. Additionally, the mechanical properties of alginates have been studied for neuroscience applications using the finite element method. Furthermore, the application of titanium alloys in dental, biotechnology, and medical fields has been explored. Studies have also been conducted on bioglass materials as a substitute for dental applications. Moreover, investigations into the use of modern ceramics with suitable mechanical and thermal properties in bioelectrical engineering have been carried out. The effect of biomechanical stimuli on cells and their characteristics has also been examined. Finally, the use of calcium silicate nanoparticles in the production of bio-composite bone substitutes has been investigated [11-12]. However, the toxicity of Ti alloys containing vanadium (V) and aluminum (Al) is a significant issue, as their low shear and wear resistance can release toxic metal ions in biological fluids, resulting in cytotoxicity and genotoxicity [12-17]. To address this issue, researchers are exploring carbon nanomaterials such as CNTs and graphene as promising nanoparticles for polymer and metal matrix composites, given their unique physical, electronic, and mechanical properties. CNTs exhibit exceptional mechanical properties, including high bending resistance, tensile strength ranging from 11 to 52 GPa, and elastic modulus ranging from 32 to 1470 GPa [18-22]. The absence of scattering counterions in their structure offers zero resistance to electron movement, making them ideal for advanced engineering applications such as field emitters, Li-ion batteries, and potential electrical contact materials. Carbon has been investigated as a reinforcing material for the past two decades and is considered a next-generation material for engineering components, particularly in the aerospace industry.

Since its discovery, graphene has been extensively researched for its physical, chemical, mechanical, optical, and electrical properties, and its potential applications have been demonstrated in nearly 100,000 scientific publications indexed by Scopus and 2,000 patents in the past year [23-27].

Table 1: Advantages and limitations of available metal biomaterials for use in scaffolds and tissue engineering implants.

Metals	Disadvantages	Advantages
SS (316L)	Low wear resistance High Meduliang MRI products because magnetism	High strength
Ti alloys	Low wear resistance Toxic alloying elements, for example, V, Al High Meduliang	High strength Equal resistance High corrosion
Co-Cr alloys	The toxicity of ions (Co-Cr	High strength.
Magnesium alloys	High Meduliang	High biocompatibility Excellent biodegradability Properties similar to the strength and malleability of human bones

However, recent research trends suggest that while CNTs and graphene have been studied extensively for material engineering applications, their potential use in medical engineering has not been adequately explored. The biocompatibility of biodegradable implants depends on the destruction mechanism of metal biomaterials, and potential risks of toxicity include cytotoxicity, tissue toxicity, allergic and immune reactions, and other immunological responses. Table 1 provides a summary of the advantages and limitations of various metal biomaterials that are currently available for use in scaffolds and tissue engineering implants. These materials have unique properties that make them suitable for specific applications.

2- Importance of Minimizing Metal Wear in Total Hip Replacement Systems

When designing a total hip replacement system, it is essential to consider the potential for metal-on-metal contact between the metal ball (femoral head), metal femoral stem, and metal cup in the acetabular part of the femur [28-33]. As a person usually takes several thousand steps a day, this metal-on-metal contact can cause wear and tear, leading to the release of metal ions and particles from the implant. Table 1 provides a summary of the advantages and limitations of available metal biomaterials for use in scaffolds and tissue engineering implants. Metal biomaterials have been widely used in orthopedic and dental applications due to their excellent mechanical properties, biocompatibility, and corrosion resistance.

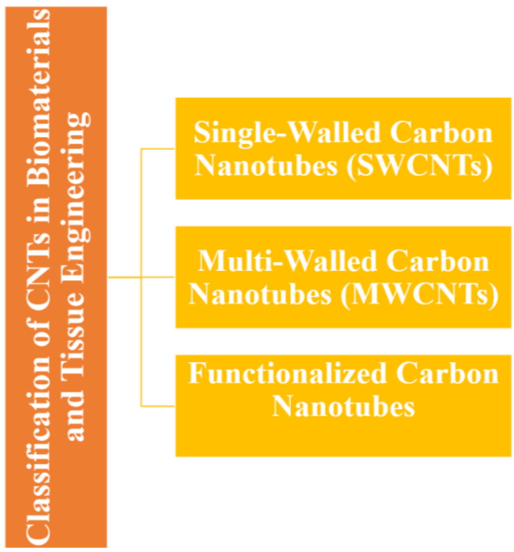

Fig. 1 CNTs are promising materials for use in biomaterials and tissue engineering

Within the discussion section, notable progress and prospective impacts of carbon nanomaterials in the realms of biomedical, food, and industrial applications are highlighted. An extensive evaluation is conducted on the present state of utilizing carbon nanomaterials, encompassing their distinct properties and successful use cases. Additionally, the discussion delves into the obstacles and constraints encountered when implementing these materials, encompassing safety apprehensions and regulatory factors. Prospects for the future are explored, centering on potential avenues and research directions to optimize the advantages of carbon nanomaterials in propelling advancements within these pivotal sectors. However, different metal biomaterials have their own advantages and limitations in terms of their physical and biological properties, which can affect their suitability for specific biomedical applications.

Fig. 1 depicts the potential of carbon nanotubes (CNTs) as a promising material for use in biomaterials and tissue engineering. CNTs are one-dimensional carbon allotropes that exhibit unique physical, chemical, and mechanical properties. These properties make them attractive for a wide range of biomedical applications, including tissue engineering, drug delivery, and biosensors. Furthermore, the release of metal ions and particles can lead to implant loosening and failure, requiring revision surgery to remove and replace the implant. Therefore, it is critical to design and manufacture hip replacement systems that minimize metal wear and reduce the potential for metal-on-metal contact to prevent adverse reactions and implant failure [34-39]. In general, no single metal biomaterial can provide all the desired features for biomedical applications. Therefore, it is crucial to explore and develop new materials that can address the key challenges associated with existing metal biomaterials. Researchers are actively investigating the development of new metal alloys for use as substitutes for hard tissue, such as cortical bone, for load-bearing applications, including bone plates, spinal rods, and artificial hip and knee joints [38-42]. An emerging research field is the development of metal alloys with adjustable Young's modulus, which can mimic the mechanical properties of natural bone and reduce the risk of stress shielding. CNTs possess exclusive mechanical properties that make them an attractive candidate for use in bone tissue engineering. The mechanical properties of CNTs can be characterized by their strength, stiffness, and toughness. CNTs have a high tensile strength ranging from 30-200 GPa, and stiffness ranging from 1-1,000 GPa, depending on their diameter and chirality. This is in contrast to human bone, which has a tensile strength and stiffness ranging from 50-150 MPa and 10-30 GPa, respectively. However, CNTs have a relatively low toughness ranging from 0.5-10 MPa·$m^{1/2}$, lower than human bone (3-20 MPa·$m^{1/2}$)). Further research is required to optimize CNT-based materials' mechanical properties for bone tissue engineering applications [41-49].

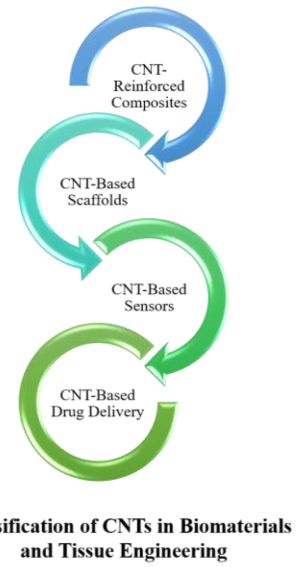

Fig. 2 Classification of CNTs in Biomaterials and Tissue Engineering

Fig. 2 shows a classification of CNTs in biomaterials and tissue engineering. CNTs are one-dimensional carbon allotropes with unique physical, chemical, and mechanical properties that make them attractive for various biomedical applications. The use of advanced manufacturing (AM) techniques, such as additive manufacturing, can also enable the production of complex and customized metal implants with enhanced mechanical properties and biocompatibility [46-52]. By developing new metal biomaterials with improved properties and performance, researchers aim to create more effective and safer biomedical devices for patients.

3- CNT and graphene for biomedical applications

These metal ions and particles can enter the bloodstream and cause toxicity and severe adverse reactions, as they are known to cause metallosis, an inflammatory reaction to the presence of metal debris in the body. CNTs are one-dimensional carbon allotropes that exhibit excellent mechanical properties, high aspect ratio, and high surface area. These properties make them attractive for a wide range of biomedical applications, including drug delivery, biosensors, and tissue engineering. In drug delivery, CNTs can be modified to encapsulate drugs and enhance their solubility, stability, and targeted delivery to specific cells or tissues. In biosensors, CNTs can be used as transducers to detect biological molecules with high sensitivity and selectivity. In tissue engineering, CNTs can be incorporated into scaffolds to enhance their mechanical properties, electrical conductivity, and cellular interactions.

Table 2: Approaches and performance of biomaterials in human body

Approaches in biomaterials	Performance	Application in human body
Implant osseointegration, stabilization, retention, removal, wear prevention.	Integration, bone formation, moduli control, degradation, resilience, anti-plaque properties.	Hip and knee joints, cardiovascular stents, heart valves, bone devices, bone, all-metal implants, surgical instruments.

Table 2 presents various approaches in biomaterials, with a focus on their performance and application in the human body. One approach involves the effective osseointegration of metal implants, which leads to the stabilization of the host bone and prevents implant loosening.

Single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNTs) are widely used in research due to their unique and promising physico-chemical properties and potential applications in various fields such as optics, sensors, biomedical, electricity, and magnetism. However, the direct exposure of CNTs to animals raises questions about their safety, and considerable research is needed to evaluate the actual nano-smitting of CNTs using different delivery methods. Recent studies have shown that different factors affect the toxicity and nanoscale activity of CNTs in the physiological environment. Graphene has also shown high absorption of extracellular proteins and serum in laboratory environments, leading to an increase in cellular adhesion of these nanomaterials [48-53]. Many words demonstrate the interdisciplinary nature of research in materials science, biomedical engineering, and medical sciences, highlighting the importance of collaboration between different fields to advance knowledge and develop new technologies for various applications [54-55]. CNT and graphene reinforced nanocomposites show promising potential for overcoming one of the most significant limitations of artificial tissues: the mismatch between the implant material and the host natural tissue. The mechanical strength of CNT and graphene makes them suitable as nano-reinforcers in composites for applications such as tissue engineering, as they can adjust the hardness and toughness of the composite [55-65].

The table provides insights into three essential mechanical properties, namely tensile strength, Young's modulus, and flexural strength. The CNT-reinforced composites demonstrate a tensile strength ranging from 500 to 900 MPa, a Young's modulus ranging from 50 to 80 GPa, and a flexural strength ranging from 400 to 600 MPa.

Table 3: the mechanical properties of CNT-reinforced composites and common composites used in medical engineering

Composite Material	Tensile Strength (MPa)	Young's Modulus (GPa)	Flexural Strength (MPa)
CNT-Reinforced Composite	500-900	50-80	400-600
Carbon Fiber Composite	1000-1500	100-150	900-1200
Glass Fiber Composite	500-800	30-40	400-600
Polymer Matrix Composite	50-200	1-10	30-100

Table 3 presents a comparative analysis of the mechanical characteristics of carbon nanotube (CNT)-reinforced composites and commonly utilized composites in the domain of medical engineering.

Numerous investigations have been carried out within the biomedical engineering domain. These studies encompass a range of topics, including the development and simulation of 3D printed scaffolds with alginate/magnesium oxide coatings, which exhibit antibacterial properties and are intended for bone tissue regeneration purposes. Furthermore, there has been a focus on exploring the mechanical and thermal characteristics of graphene-CuO nanocomposites. Another research endeavor involved conducting a bibliometric analysis of dental preprints that were published in the year 2022. Additionally, simulation studies were conducted to evaluate the potential of 3D printed scaffolds incorporating alginate/carbon nanotubes for applications in bone engineering. Moreover, researchers have delved into the utilization of 3D bioprinting techniques for dental pulp regeneration, specifically through the implementation of porous architectural designs. Lastly, the fabrication and analysis of calcium-zirconia scaffolds infused with magnetic nanoparticles for the treatment of bone cancer have been thoroughly investigated. Additionally, their significant conductive properties make them useful for electrically stimulating tissues to speed up the formation and repair of new bone [66-72]. CNT and graphene enhanced conductive nano-biomaterials also increase the absorption of extracellular matrix (ECM) proteins, leading to an increase in the expression of osteogenic markers and the production of related growth factors. CNT and graphene reinforced nanocomposites show great potential for use in bone tissue engineering and other biomedical applications [68-72].

4- Conclusion

This study was carried out with the aim of critically examining the potential, recent developments, challenges and future research directions in relation to CNT and graphene as nano enhancers in existing metal biomaterials. It can be concluded that these carbon nanomaterials have extraordinary potential to be used as biomaterials for bone tissue engineering. In spite of the controversial issues about nanosmitting and endocytosis of CNT and graphene, their significant and unique mechanical and biological properties strongly support their use in biomedical applications. Recent trends in biomedical, pharmaceutical and tissue engineering fields show that CNT and graphene can be considered very effective and safe materials. With the available literature on the biomedical applications of CNT and graphene, they cannot yet be judged as good candidate materials for bone tissue engineering. However, recent studies on CNT and graphene-based materials for biomedical applications did not show significant evidence of biological hazards. So, biocompatibility, biodegradability, bioactivity and mechanical properties of CNT and graphene have been critically examined with the aim of converting their properties to biomedical applications. A detailed discussion on the key requirements for implants and tissue engineering scaffolds related to the mechanical properties of CNT and graphs with the aim of converting their properties to biomedical applications is a critical review. It has been downloaded. A detailed discussion of the key requirements for implants and tissue engineering scaffolds in relation to the mechanical properties of CNT and grafting with the aim of converting their properties to biomedical applications is a critical review. It has been decided. A detailed discussion of the key requirements for implants and tissue engineering scaffolds in relation to the unique properties of CNT and graphene is necessary to translate this promising nanomaterial into clinical applications. It is Although the results obtained from *in vitro* and *in vivo* biocompatibility studies on CNTs and graphene are encouraging, more comprehensive and systematic studies are still needed to understand their long-term biological effects. It is necessary. Continuous *in vivo* studies to understand the nanoscale of this carbon nanomaterial can pave the way for the translation of this class of materials into approved clinical applications. At present, one of the main reasons for the inability of these nanomaterials to be converted into clinically approved applications is the lack of suitable in vivo studies to evaluate their nanosize. In addition to other biomedical applications Who, implants and scaffolds were considered because there is a small possibility that this nano enhancement Metal matrices are directly exposed to living organisms. Despite the recent technological advances that can easily assess the biosafety of such carbon nanomaterials, global efforts are determined to develop the user. This requires precise and sophisticated engineering. Scientific methods for reducing the nanotoxicological effect of CNT and graphene are also characteristic.

References

[1] Sahithi, K., Swetha, M., Ramasamy, K., Srinivasan, N., & Selvamurugan, N. (2010).

Polymeric composites containing carbon nanotubes for bone tissue engineering. International journal of biological macromolecules, 46(3), 281-283.

[2] Karimianmanesh, M., Azizifard, E., Javidanbashiz, N., Latifi, M., Ghorbani, A., & Shahriari, S. (2021). Feasibility study of mechanical properties of alginates for neuroscience application using finite element method. Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering, 13(3), 53-62.

[3] Alibabaei, S., Kasiri-Asgarani, M., & Bakhsheshi-Rad, H. (2019). Investigating the effect of solid solution treatment on the corrosion properties of biodegradable Mg-Zn-RE-xCa (x = 0, 2.5) alloy. Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering, 12(4), 67-80.

[4] Malekipour Esfahani, M. H., Sharifinezhad, N., Hemati, M., & Gholami, A. M. (2021). Evaluation of mechanical properties of bioglass materials for dentistry application. Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering, 13(4), 19-29.

[5] Heydari, S., Sadat Mirinejad, M., Malekipour Esfahani, M. H., Karimian, F., Attaeyan, A., & Latifi, M. (2021). A brief review on titanium alloy for dental, biotechnology and biomedical applications. Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering, 13(2), 47-58.

[6] Heydari, S., Attaeyan, A., Bitaraf, P., Gholami, A. M., & Kamyab Moghadas, B. (2021). Investigation of modern ceramics in bioelectrical engineering with proper thermal and mechanical properties. Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering, 13(3), 43-52.

[7] Ghorbani, A., Shahriari, S., & Gholami, A. M. (2021). Investigation of cell biomechanics and the effect of biomechanical stimuli on cancer and their characteristics. Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering, 13(4), 67-79.

[8] Aghdam, H. A., Sanatizadeh, E., Motififard, M., Aghadavoudi, F., Saber-Samandari, S., Esmaeili, S., ... & Khandan, A. (2020). Effect of calcium silicate nanoparticle on surface feature of calcium phosphates hybrid bio-nanocomposite using for bone substitute application. Powder Technology, 361, 917-929.

[9] Hoseini, M., Malekipour, M. R., & Shirani, F. (2022). The Effect of Application of Sonic Vibration on the Bond Strength of Glass Fiber Post to Root Dentin using Duo-link and Theracem cements: An In Vitro Study. Dental Hypotheses, 13(1), 10.

[10] Haghighat, A., Momeni, H., Yeganeh, F., Haghani, Y., & Nazarifar, A. M. (2022). Nasal Reconstruction due to Basal-Cell Carcinoma using Dental Implants: A Case Report. Dental Hypotheses, 13(1), 24.

[11] Forouzan, M. R., Heidari, A., & Golestaneh, S. J. (2009). FE simulation of submerged arc welding of API 5L-X70 straight seam oil and gas pipes.

[12] Moradi, A., Heidari, A., Amini, K., Aghadavoudi, F., & Abedinzadeh, R. (2021). Molecular modeling of Ti-6Al-4V alloy shot peening: the effects of diameter and velocity of shot particles and force field on mechanical properties and residual stress. Modelling and Simulation in Materials Science and Engineering, 29(6), 065001.

[13] Heidari, A., Forouzan, M. R., & Akbarzadeh, S. (2014). Effect of friction on tandem cold rolling mills chattering. ISIJ International, 54(10), 2349-2356.

[14] Moradi, A., Heidari, A., Amini, K., Aghadavoudi, F., & Abedinzadeh, R. (2022). The effect of shot peening time on mechanical properties and residual stress in Ti-6Al-4V alloy. Metallurgical Research & Technology, 119(4), 401.

[15] Momeni, M., Amini, K., Heidari, A., & Khodaei, M. (2022). Evaluation the properties of polycaprolactone/fluorapatite nano-biocomposite. Journal of Bionic Engineering, 19(1), 179-187.

[16] Khaki, S., Heidari, A., & Kolahdooz, A. (2019). Optimizing Friction Stir Welding Process for Enhancing Strength and Hardness using Taguchi Multi-Objective Function Method. ADMT Journal, 12(3), 25-33.

[17] Li, X., Heidari, A., Nourbakhsh, S. M., Mohammadi, R., & Semiromi, D. (2022). Design and fabrication of elastic two-component polymer-metal disks using a 3D printer under different loads for the lumbar spine. Polymer Testing, 112, 107633.

[18] Mansouri, A., Heidari, A., Karimian, F., Gholami, A. M., Latifi, M., & Shahriari, S. (2021). Molecular simulation for prediction of mechanical properties of polylactic acid polymer for biotechnology applications. Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering, 13(4), 31-40.

[19] Hajibagheri, H. R., Heidari, A., & Amini, R. (2021). An experimental determination of fracture toughness of API X46 steel pipeline using single edge bend and crack assessments by failure assessment diagrams. Journal of Stress Analysis, 5(2), 41-52.

[20] Samimi, P., Kazemian, M., Shirban, F., Alaei, S., & Khoroushi, M. (2018). Bond strength of composite resin to white mineral trioxide aggregate: Effect of different surface treatments. Journal of Conservative Dentistry: JCD, 21(4), 350.

[21] Rafieian, S., Hashemian, M., & Pirmoradian, M. (2018). Buckling analysis of double-layer piezoelectric nanoplates surrounded by elastic foundations and thermal environments considering nonlocal and surface energy models. Journal of Mechanics, 34(4), 483-494.

[22] Raji, Z., Hosseini, M., & Kazemian, M. (2022). Micro-shear bond strength of composite to deep dentin by using mild and ultra-mild universal adhesives. Dental Research Journal, 19.

[23] Hosseini, M., Raji, Z., & Kazemian, M. (2023). Microshear bond strength of composite to superficial dentin by use of universal adhesives with different pH values in self-etch and etch & rinse modes. Dental Research Journal, 20.

[24] Zadeh Dadashi, M., Kazemian, M., & Malekipour Esfahani, M. (2023). Color Match of Porcelain Veneer Light-Cure Resin Cements with Their Respective Try-in Pastes: Chemical Stability. Nanochemistry Research, 8(3), 205-214.

[25] Kazemian, M. (2017). An In-Vitro Study of the Antibacterial Efficacy of Cavity Liners Against Streptococcus Mutans and Lactobacillus Casei. Journal of Research in Dental and Maxillofacial Sciences, 2(2), 23-28.

[26] Mahale, R. S., Shamanth, V., Sharath, P. C., Shashanka, R., & Hemanth, K. (2021). A review on spark plasma sintering of duplex stainless steels. Materials Today: Proceedings, 45, 138-144.

[27] Chaudhari, V., Bodkhe, V., Deokate, S., Mali, B., & Mahale, R. (2019). Parametric optimization of TIG welding on SS 304 and MS using Taguchi approach. Int. Res. J. Eng. Technol, 6(5), 880-885.

[28] RaviShankar, S., & Mahale, R. (2015). A study on magneto rheological fluids and their applications. International Research Journal of Engineering and Technology, 2(4), 2023-2028.

[29] Patil, A., Banapurmath, N., Hunashyal, A. M., Meti, V., & Mahale, R. (2022). Development and Performance analysis of Novel Cast AA7076-Graphene Amine-Carbon Fiber Hybrid Nanocomposites for Structural Applications. Biointerface Research in Applied Chemistry, 12(2), 1480-1489.

[30] Chikkegouda, S. P., Gurudath, B., Sharath, B. N., Karthik, S., & Mahale, R. S. (2022). Mechanical and tribological characteristics of aluminium 2618 matrix composite reinforced with boron carbide. Biointerface Research in Applied Chemistry, 12(4).

[31] Barbaz-Isfahani, R., Dadras, H., Taherzadeh-Fard, A., Zarezadeh-Mehrizi, M. A., Saber-Samandari, S., Salehi, M., & Liaghat, G. (2022). Synergistic effects of incorporating various types of nanoparticles on tensile, flexural, and quasi-static behaviors of GFRP composites. Fibers and Polymers, 23(7), 2003-2016.

[32] Dadras, H., Barbaz-Isfahani, R., Saber-Samandari, S., & Salehi, M. (2022). Experimental and multi-scale finite element modeling for evaluating healing efficiency of electro-sprayed microcapsule based glass fiber-reinforced polymer composites. Polymer Composites, 43(9), 5929-5945.

[33] Abedinzadeh, R., & Faraji Nejad, M. (2021). Effect of embedded shape memory alloy wires on the mechanical behavior of self-healing graphene-glass fiber-reinforced polymer nanocomposites. Polymer Bulletin, 78(6), 3009-3022.

[34] Torkan, E., & Pirmoradian, M. (2019). Efficient higher-order shear deformation theories for instability analysis of plates carrying a mass moving on an elliptical path. Journal of Solid Mechanics, 11(4), 790-808.

[35] Abedinzadeh, R., Norouzi, E., & Toghraie, D. (2021). Experimental investigation of machinability in laser-assisted machining of aluminum-based nanocomposites. Journal of Materials Research and Technology, 15, 3481-3491.

[36] Zadeh, A. R., Eghbal, A. F., Mirghazanfari, S. M., Ghasemzadeh, M. R., Nassireslami, E., & Donyavi, V. (2022). Nigella sativa extract in the treatment of depression and serum Brain-Derived Neurotrophic Factor (BDNF) levels. Journal of Research in Medical Sciences: The Official Journal of Isfahan University of Medical Sciences, 27.

[37] Hosseini, S., Golaghaei, A., Nassireslami, E., Pourbadie, N., Rahimzadegan, M., & Mohammadi, S. (2019). Neuroprotective effects of lipopolysaccharide and naltrexone co-preconditioning in the photothrombotic model of unilateral selective hippocampal ischemia in rat. Acta Neurobiologiae Experimentalis, 79(1), 73-85.

[38] Elahabaadi, E., Salarian, A. A., & Nassireslami, E. (2022). Design, synthesis, and molecular docking of novel hybrids of coumarin-dithiocarbamate alpha-glucosidase inhibitors targeting type 2 diabetes mellitus. Polycyclic Aromatic Compounds, 42(7), 4317-4327.

[39] Afshary, K., Chamanara, M., Talari, B., Rezaei, P., & Nassireslami, E. (2020). Therapeutic effects of minocycline pretreatment in the locomotor and sensory complications of spinal cord injury in an animal model. Journal of Molecular Neuroscience, 70, 1064-1072.

[40] Maghsoudlou, M. A., Nassireslami, E., Saber-Samandari, S., & Khandan, A. (2020). Bone regeneration using bio-nanocomposite tissue reinforced with bioactive nanoparticles for femoral defect applications in medicine. Avicenna Journal of Medical Biotechnology, 12(2), 68.

[41] Eslami, M., Mokhtarian, A., Pirmoradian, M., Seifzadeh, A., & Rafiaei, M. (2020). Design and fabrication of a passive upper limb rehabilitation robot with adjustable automatic balance based on variable mass of end-effector. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42, 1-8.

[42] Nassireslami, E., Motififard, M., Kamyab Moghadas, B., Hami, Z., Jasemi, A., Lachiyani, A., ... & Khandan, A. (2021). Potential of magnetite nanoparticles with biopolymers loaded with gentamicin drug for bone cancer treatment. Journal of Nanoanalysis, 8(3), 188-198.

[43] Esfahani, O. T., & Moshayedi, A. J. (2014). Accuracy of the Positioning Systems for the Tracking of Alzheimer's Patients-A Review. International Journal of Applied Electronics in Physics & Robotics, 2(2), 10-16.

[44] Moshayedi, A. J., Li, J., Sina, N., Chen, X., Liao, L., Gheisari, M., & Xie, X. (2022). Simulation and validation of optimized pid controller in agv (automated guided vehicles) model using pso and bas algorithms. Computational Intelligence and Neuroscience, 2022.

[45] Torkan, E., Pirmoradian, M., & Hashemian, M. (2019). Dynamic instability analysis of moderately thick rectangular plates influenced by an orbiting mass based on the first-order shear deformation theory. Modares Mechanical Engineering, 19(9), 2203-2213.

[46] Moshayedi, A. J., & Gharpure, D. C. (2012, May). Development of position monitoring system for studying performance of wind tracking algorithms. In ROBOTIK 2012; 7th German Conference on Robotics (pp. 1-4). VDE.

[47] Ghomi, F., Daliri, M., Godarzi, V., & Hemati, M. (2021). A novel investigation on the characterization of bioactive glass cement and chitosan-gelatin membrane for jawbone tissue engineering. Journal of Nanoanalysis, 8(4), 292-301.

[48] Foroutan, S., Hashemian, M., Khosravi, M., Nejad, M. G., Asefnejad, A., Saber-Samandari, S., & Khandan, A. (2021). A porous sodium alginate-CaSiO 3 polymer reinforced with graphene nanosheet: fabrication and optimality analysis. Fibers and Polymers, 22, 540-549.

[49] Biazar, E., Beitollahi, A., Rezayat, S. M., Forati, T., Asefnejad, A., Rahimi, M., ... & Heidari, M. (2009). Effect of the mechanical activation on size reduction of crystalline acetaminophen drug particles. International Journal of Nanomedicine, 283-287.

[50] Tayebi, P., Asefnejad, A., & Khonakdar, H. A. (2021). Water-based polyurethane/functionalized chitosan/zinc oxide nanoparticles nanocomposites: physical, mechanical and biocompatibility properties. Polymer-Plastics Technology and Materials, 60(13), 1474-1489.

[51] Davani, P. P., Kloub, A. W. M., & Ghadiri Nejad, M. (2020). Optimizing the first type of U-shaped assembly line balancing problems. Annals of Optimization Theory and Practice, 3(4), 65-82.

[52] Ghadirinejad, M. A. Z. Y. A. R., & Mosallaeipour, S. (2013). A new approach to optimize a flexible manufacturing cell. In 1st international conference on new directions in business, management, finance and economics (Vol. 38).

[53] Cheng, Y., Morovvati, M. R., Huang, M., Shahali, M., Saber-Samandari, S., Angili, S. N., ... & Toghraie, D. (2021). A multilayer biomimetic chitosan-gelatin-fluorohydroxyapatite cartilage scaffold using for regenerative medicine application. Journal of Materials Research and Technology, 14, 1761-1777.

[54] Du, X., Dehghani, M., Alsaadi, N., Nejad, M. G., Saber-Samandari, S., Toghraie, D., ... & Nguyen, H. C. (2022). A femoral shape porous scaffold bio-nanocomposite fabricated using 3D printing and freeze-drying technique for orthopedic application. Materials Chemistry and Physics, 275, 125302.

[55] Hashemi, S. A., Esmaeili, S., Ghadirinejad, M., Saber-Samandari, S., Sheikhbahaei, E., Kordjamshidi, A., & Khandan, A. (2020). Micro-finite element model to investigate the mechanical stimuli in scaffolds fabricated via space holder technique for cancellous bone. ADMT Journal, 13(1), 51-58.

[56] Bagherifard, A., Joneidi Yekta, H., Akbari Aghdam, H., Motififard, M., Sanatizadeh, E., Ghadiri Nejad, M., ... & Khandan, A. (2020). Improvement in osseointegration of tricalcium phosphate-zircon for orthopedic applications: an in vitro and in vivo evaluation. Medical & Biological Engineering & Computing, 58, 1681-1693.

[57] Ghadirinejad, M., Atasoylu, E., Izbirak, G., & Matina, G. S. (2016). A stochastic model for the ethanol pharmacokinetics. Iranian journal of public health, 45(9), 1170.

[58] Sun, C., Yarmohammadi, A., Isfahani, R. B., Nejad, M. G., Toghraie, D., Fard, E. K., ... & Khandan, A. (2021). Self-healing polymers using electrosprayed microcapsules containing oil: Molecular dynamics simulation and experimental studies. Journal of Molecular Liquids, 325, 115182.

[59] Salmani, M. M., Hashemian, M., Yekta, H. J., Nejad, M. G., Saber-Samandari, S., & Khandan, A. (2020). Synergic effects of magnetic nanoparticles on hyperthermia-based therapy and controlled drug delivery for bone substitute application. Journal of Superconductivity and Novel Magnetism, 33, 2809-2820.

[60] Ghayour, H., Abdellahi, M., Nejad, M. G., Khandan, A., & Saber-Samandari, S. (2018). Study of the effect of the Zn 2+ content on the anisotropy and specific absorption rate of the cobalt ferrite: the application of Co 1− x Zn x Fe 2 O 4 ferrite for magnetic hyperthermia. Journal of the Australian Ceramic Society, 54, 223-230.

[61] Khandan, A., Ozada, N., Saber-Samandari, S., & Nejad, M. G. (2018). On the mechanical and biological properties of bredigite-magnetite (Ca7MgSi4O16-Fe3O4) nanocomposite scaffolds. Ceramics International, 44(3), 3141-3148.

[62] Kordjamshidi, A., Saber-Samandari, S., Nejad, M. G., & Khandan, A. (2019). Preparation of novel porous calcium silicate scaffold loaded by celecoxib drug using freeze drying technique: Fabrication,

characterization and simulation. Ceramics International, 45(11), 14126-14135.

[63] Asgari, F., Minooei, A., Abdolahi, S., Shokrani Foroushani, R., & Ghorbani, A. (2021). A new approach using Machine Learning and Deep Learning for the prediction of cancer tumor. Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering, 13(4), 41-51.

[64] Malekipour Esfahani, M. H., Ghorbani, A., & Latifi, M. (2023). Evaluation of lipid nanocarriers in the form of SLN and their application in drug delivery and medical science. Nanochemistry Research, 8(1), 57-70.

[65] Ehsani, A., Mahale, R. S., Shayegan, S., Attaeyan, A., Ghorbani, A., Vasanth, S., ... & Asefnejad, A. (2022). A review of the treatment of bone tumours by hyperthermia using magnetic nanoparticles. Journal of Nanoanalysis.

[66] Esmaeili, S., Shahali, M., Kordjamshidi, A., Torkpoor, Z., Namdari, F., Saber-Samandari, S., ... & Khandan, A. (2019). An artificial blood vessel fabricated by 3D printing for pharmaceutical application. Nanomedicine Journal, 6(3), 183-194.

[67] Shirani, K., Sheikhbahaei, E., Torkpour, Z., Nejad, M. G., Moghadas, B. K., Ghasemi, M., ... & Khandan, A. (2020). A narrative review of COVID-19: the new pandemic disease. Iranian Journal of Medical Sciences, 45(4), 233.

[68] Farazin, A., Torkpour, Z., Dehghani, S., Mohammadi, R., Fahmy, M. D., Saber-Samandari, S., ... & Khandan, A. (2021). A review on polymeric wound dress for the treatment of burns and diabetic wounds. International Journal of Basic Science in Medicine, 6(2), 44-50.

[69] Angili, S. N., Morovvati, M. R., Kardan-Halvaei, M., Saber-Samandari, S., Razmjooee, K., Abed, A. M., ... & Khandan, A. (2023). Fabrication and finite element simulation of antibacterial 3D printed Poly L-lactic acid scaffolds coated with alginate/magnesium oxide for bone tissue regeneration. *International Journal of Biological Macromolecules*, *224*, 1152-1165.

[70] Safaei, M., Abedinzadeh, R., Khandan, A., Barbaz-Isfahani, R., & Toghraie, D. (2023). Synergistic effect of graphene nanosheets and copper oxide nanoparticles on mechanical and thermal properties of composites: Experimental and simulation investigations. *Materials Science and Engineering: B*, *289*, 116248.

[71] Mirmohammadi, H., Kolahi, J., & Khandan, A. (2023). Bibliometric Analysis of Dental Preprints which Published in 2022. *Dental Hypotheses*, *14*(1), 1-2.

[72] Moarrefzadeh, A., Morovvati, M. R., Angili, S. N., Smaisim, G. F., Khandan, A., & Toghraie, D. (2022). Fabrication and finite element simulation of 3D printed poly L-lactic acid scaffolds coated with alginate/carbon nanotubes for bone engineering applications. *International Journal of Biological Macromolecules*, *224*, 1496-1508.

[73] Iranmanesh, P., Ehsani, A., Khademi, A., Asefnejad, A., Shahriari, S., Soleimani, M., ... & Khandan, A. (2022). Application of 3D bioprinters for dental pulp regeneration and tissue engineering (porous architecture). *Transport in Porous Media*, *142*(1-2), 265-293.

[74] Jasemi, A., Moghadas, B. K., Khandan, A., & Saber-Samandari, S. (2022). A porous calcium-zirconia scaffolds composed of magnetic nanoparticles for bone cancer treatment: Fabrication, characterization and FEM analysis. *Ceramics International*, *48*(1), 1314-1325.