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Recent Review on Nanoparticles-Doped Polyethylene Oxide for Biomedical and Industrial Applications

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Polymers, such as polyethylene oxide (PEO), include exceptional characteristics, which made them as promising materials for a variety of biomedical, electronics and optics fields. Metal oxide and nitride nanoparticles have enormous applications in various approaches too. This article comprised a recent review on PEO doped with metal oxide and nitride nanoparticles, such as CeO_2 and Si_3N_4. The previous studies illustrated that the nanocomposites of PEO doped with metal oxide or nitride nanoparticles have numerous applications in the biomedical and industrial fields due to their physical and chemical properties.

Полімери, такі як поліетиленоксид (ПЕО), мають виняткові характеристики, що робить їх перспективними матеріялами для різних галузей біомедицини, електроніки й оптики. Наночастинки оксидів і нітридів металів мають величезне застосування в різних підходах також. Ця стаття містить нещодавній огляд ПЕО, леґованого наночастинками оксидів і нітридів металів, таких як CeO_2 та Si_3N_4. Попередні дослідження показали, що нанокомпозити ПЕО, леґованого наночастинками оксидів або нітридів металів, мають численні застосування в біомедичній і промисловій сферах завдяки їхнім фізичним і хемічним властивостям.

Key words: polyethylene oxide, Si_3N_4 nitride, CeO_2 oxide.

Ключові слова: поліетиленоксид, нітрид Si_3N_4, оксид CeO_2.

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1. INTRODUCTION

Polymeric materials occupy every corner of our life and are actively used in many technologies [1]. Polymer materials are widely used in various devices as insulating materials and for optoelectronic applications. This is owing to their singular properties, such as high flexibility, lightweight, and ability to be fabricated with low cost and at low temperatures [2]. The field of polymer additives has garnered significant attention in today's materials research; in view of this, it is essential to note that the dopant modifies the structure of the polymer and, hence, its properties [3]. Polymer nanocomposites are burgeoning rapidly as a multidisciplinary research sector, whose results could widen the applications of polymers to the great of industrial benefits [4]. Polymer nanocomposites have polymer matrix reinforced with nanosize phase (nanofillers), such as nanoparticles (NPs), nanofibres, nanotubes, nanosheets, *etc.* [5]. The polymer nanocomposites heavily rely on geometry, size distribution, aggregation and surface chemistry of organic/inorganic nanoparticles, as well as matrix–nanoparticle interactions. However, the characteristics of nanocomposites were found to depend on the content of nanofillers, the type of nanoparticles, nature to bridge chemically and physically with the polymer matrix [6]. The polymer nanocomposites have become an important candidate in many applications including optical integrated circuits, EM detector, drug delivery, automobiles, sensors, injection moulded products, membranes, adhesives, coatings, aerospace, fire-retardants, medical devices, consumer goods, packaging materials, *etc.* [7].

2. POLYMER STRUCTURE

Polymers are produced from monomers through polymerization [8]. Polymers are mainly comprised of similar or identical units joined together. The unit forming the repetitive pattern is called a monomer or mer. Polymers are long-chain molecules of a very high molecular weight, often measured in the hundreds of thousands. Therefore, the term 'macromolecules' is frequently used, when referring to polymeric materials [9]. The properties of polymers depend on the chemistry of their constituent monomers, as well as on how these monomers combine with each other into the polymer architecture or molecular structure. Due to its importance in determining properties, polymers are often classified according to their molecular structure. Important classes include linear chain, branched, and networked polymers [10]. The monomers that make up linear polymers are linked in a long straight chain. There are no side chains on these chains, *e.g.*, polyethene, nylons, polyesters, PVC, *etc*. Their molecules are closely packed and have melting point, tensile strength, and high density. As for the branched polymers, they have a straight long chain with different side chains.

Their molecules are irregularly packed, hence, they have melting point, tensile strength, and low density, e.g., polypropylene (side chain $-CH_3$), glycogen and amylopectin, in the case of network or cross-linked polymers. In these monomeric units, they are linked together to constitute a three dimensional network. The links involved are called cross-links. They are rigid, hard, and brittle due to their network structure, *e.g.*, maia mine, bakelite, vulcanized rubber, formaldehyde resins, *etc.* [11].

2.1. Classification of Polymers Based on Source

Polymers may be divided into three types [12].

a. Natural polymer. These polymers are found in nature generally from plants and animals sources. Some examples include proteins, starch, cellulose, and resins.

b. Semi-synthetic polymer. These polymers are produced from natural polymers by simple chemical processing aimed at altering the physical characteristics of natural polymers, such as starch.

c. Synthetic polymer. The fibres, which are synthesized in laboratory by polymerization of simple chemical molecules, are termed synthetic polymers, for example: polyethene, nylon, synthetic rubber, polystyrene, teflon, PVC, *etc*.

2.2. Classification of Polymers Based on Thermal Response

a. Thermoplastic polymers. Thermoplastic resins are polymers linked by intermolecular interactions or van der Waals forces forming a linear or branched molecular structure. The molecular structure, whether linear or branched, only imposes a relatively small restriction for the motion of molecular chains. As a result, thermoplastics are remeltable and tractable upon the application of pressure and heat after curing [13].

b. Thermosetting polymers. Thermosets or network polymers comprise of densely cross-linked networks, where the chain segments between cross-links have low mobility. The chain molecules are linked together by strong covalent bonds even between the chains forming a continuous network. The covalent bonds prevent chain segments from slipping past each other. Consequently, such a network can neither be dissolved nor become molten [14].

3. POLYETHYLENE OXIDE (PEO)

PEO is a linear semi-crystalline polymer that has many features, such as being flexible, non-toxic [16], low cost [17], and watersoluble [18]. It has a general chemical structure of $[OCH_2CH_2]_n$, where n is the degree of polymerization, which ranges between 2000 and 100 000 [19]. With a molecular formula of $C_{2n+2}H_{4n+6}O_{n+2}$ [20], PEO is a non-ionic homopolymer of ethylene oxide [21]. It is a white to off-white powder obtainable in several grades, varying in viscosity profile in an aqueous isopropyl alcohol solution. It may contain a suitable antioxidant [22–24].

Polyethylene oxide polymers are utilized in a wide range of applications and are classified into two groups based on their molecular weight. The liquid and waxy polymers with low molecular weights of about 6 000–8 000 g/mole are widely used in cosmetics (powders, sticks, cakes, lotions and creams), formulating pharmaceuticals (dry binders, suppository bases, ointments, tablet coatings lubrication in the formulating and manufacture of compressed tablets), sizing and humectants. The use of high molecular weight polymers ($\geq 10^5$) is contingent upon their solubility, rheology, and thermoplastic nature. These polymers have been utilized as flocculants for finely dispersed solids in water, as dispersants for cementitious materials, and in miscellaneous applications [26].

4. SILICON NITRIDE (Si_3N_4)

Silicon nitride (Si_3N_4) is a significant ceramic material owing to its chemical, electronic, and mechanical properties [27]. Silicon nitride has strong resistance against thermal shock, low mechanical stress, and high melting temperature. Due to its exceptional mechanical properties at elevated temperatures, it has been regarded as an exemplary material for applications in cutting tools and engine components. It has a sizeable electronic gap, a high-energy barrier for impurity diffusion, a high resistance against radiation and a high dielectric constant. These properties led to applications in microelectronic devices as charge storage medium in non-volatile memories as a gate dielectric in thin-film transistors and in solar cells [28]. Additionally, other engineering applications are also under consid-

TABLE. Physical and mechanical characteristics of Si_3N_4 [30].

Characteristic	Si_3N_4
Melting point, °C	1900
Density, g/cm^3	3.17–3.20
Hardness, GPa	18
Thermal conductivity, W/(m·K)	10–162
Fracture toughness, MPa·m$^{1/2}$	2–8
Crystal structure	hexagonal

eration, such as industrial heat exchangers, as wear-resistant material in metals processing, energy conversion systems and as material for ball and roller bearings [29]. Table presents the physical and mechanical characteristics of Si_3N_4 [30].

5. CERIUM DIOXIDE (CeO_2)

The role of cerium oxide (ceria) in contemporary technological applications is multipurpose and of steadily increasing importance [31]. Cerium dioxide (CeO_2) is one of the most significant rare earth materials [32]. Amongst nanoparticles, CeO_2 NPs have attracted much attention for their high stability, biocompatibility and surface chemistry. CeO_2 nanoparticles exhibit transparency in the visible region and possess a refractive index of 2.2 at a wavelength of 632 nm. Pure CeO_2 exhibits a wide indirect optical band gap and wide energy-band gap that operates effectively in the ultraviolet (UV) region. Consequently, it is a highly suitable option for many optical and electrical applications [33]. CeO_2 has several applications in the field of corrosion prevention, electromagnetic shielding, electrochemical cells, thermal coatings, photoelectrical and optical properties [34]. It is mostly used in the fabrication of sensors, catalysis, cells, drug delivery careers, therapeutics agents, and antiparasitic ointments [35]. The nanocomposites of organic/inorganic materials or inorganic/inorganic were created to usage in various fields involving electronics and optoelectronics [36–50], optical fields [51–60], antibacterial agents [61–71], sensors [72–79], energy storage [80–88].

6. CONCLUSION

The current work comprised a recent review on PEO doped with metal oxide or nitride nanoparticles. The previous studies illustrated that the nanocomposites of PEO doped with metal oxide or nitride nanoparticles have numerous applications in the biomedical and industrial fields.

REFERENCES

1. Jiancheng Luo, Zoriana Demchuk, Xiao Zhao, Tomonori Saito, Ming Tian, Alexei P. Sokolov, and Peng-Fei Cao, *Matter*, **5**, Iss. 5: 1391 (2022); doi:10.1016/j.matt.2022.04.007
2. Wasan Al-Taa'y, Mohammed Abdul Nabi, Rahimi M. Yusop, Emad Yousif, Bashar Mudhaffar Abdullah, Jumat Salimon, Nadia Salih, and Saiful Irwan Zubairi, *Int. J. Polym. Sci.*, **2014**: Article ID 697809 (2014);

doi:10.1155/2014/697809
3. Alaa J. Kadham, Dalal Hassan, Najlaa Mohammad, and Ahmed Hashim Ahyasari, *Bull. Electr. Eng. Informatics*, **7**, No. 1: 28 (2018); doi:10.11591/eei.v7i1.839
4. Amara Nasir, Ayesha Kausar, and Ayesha Younus, *Polym. — Plast. Technol. Eng.*, **54**, Iss. 4: 325 (2015); doi:10.1080/03602559.2014.958780
5. S. K. Sharma, J. Prakash, K. Sudarshan, D. Sen, S. Mazumder, and P. K. Pujari, *Macromolecules*, **48**, No. 16: 5706 (2015); doi:10.1021/acs.macromol.5b01095
6. S. Ningaraju, A. P. G. Prakash, and H. B. Ravikumar, *Solid State Ionics*, **320**: 132 (2018); doi:10.1016/j.ssi.2018.03.006
7. M. T. Rahman, Md. Asadul Hoque, G. T. Rahman, M. A. Gafur, Ruhul A. Khan, and M. Khalid Hossain, *Results Phys.*, **13**: 102264 (2019); doi:10.1016/j.rinp.2019.102264
8. G. Murtaza, S. H. Bukhari, L. Ali, S. Z. Ilyas, A. Hakeem, M. N. Usmani, G. Mustafa, and F. Rehman, *Dig. J. Nanomater. Biostructures*, **14**, No. 1: 101 (2019).
9. R. A. Patil, N. H. Aloorkar, A. S. Kulkarni, and D. J. Ingale, *Int. J. Pharm. Sci. Nanotechnol.*, **5**, Iss. 2: 1675 (2012); doi:10.37285/ijpsn.2012.5.2.3
10. Chunyu Li and Alejandro Strachan, *J. Polym. Sci. Part B: Polym. Phys.*, **53**, Iss. 2: 103 (2015); doi:10.1002/polb.23489
11. Nuha Salih Mustafa, Mohammed A. Ali Omer, Mohamed E. M. Garlnabi, and Hamed A. Ismail, *Int. J. Sci. Res.*, **5**, Iss. 8: 212 (2016); doi:10.21275/art2016772
12. K. Kaushik, R. B. Sharma, and S. Agarwal, *Int. J. Pharm. Sci. Rev. Res.*, **37**, Iss. 2: 30 (2016).
13. Yue Liu, Bernd Zwingmann, and Mike Schlaich, *Polymers*, **7**, Iss. 10: 2078 (2015); doi:10.3390/polym7101501
14. O. Yalukova and I. Sárady, *Compos. Sci. Technol.*, **66**, Iss. 10: 1289 (2006); doi:10.1016/j.compscitech.2005.11.002
15. M. Kazemi, S. F. Kabir, and E. H. Fini, *Resour. Conserv. Recycl.*, **174**: 105776 (2021); doi:10.1016/j.resconrec.2021.105776
16. Ghayah M. Alsulaim and Ayman A. Elamin, *J. Compos. Sci.*, **7**, Iss. 6: 221 (2023); doi:10.3390/jcs7060221
17. Jan Lukas Storck, Marius Dotter, Bennet Brockhagen, and Timo Grothe, *Crystals*, **10**, Iss. 12: 1158 (2020); doi:10.3390/cryst10121158
18. Nataša Stipanelov Vrandečić, Matko Erceg, Miće Jakić, and Ivka Klarić, *Thermochim. Acta*, **498**, Iss. 1–2: 71 (2010); doi:10.1016/j.tca.2009.10.005
19. Hafiz Ahmad, M'hamed Boutaous, Shihe Xin, Hervé Pabiou, and Dennis A. Siginer, *ASME. J. Fluids Eng.*, **145**, Iss. 2: 021204 (2023); doi:10.1115/1.4056160
20. A. Nistor, G. Câmpeanu, N. Atanasiu, N. Chiru, and D. Karacsony, *Stud. Univ. Vasile Goldis' Arad. Ser. Stiint. Vietii (Life Sci. Ser.)*, **21**, No. 2: 383 (2011).
21. Kamol Dey, Ruhul A. Khan, Ruhul A. Khan and A. M. Sarwaruddin Chowdhury, *J. Thermoplast. Compos. Mater.*, **25**, Iss. 7: 807(2012); doi:10.1177/0892705711413543
22. Mohammad Reza Talaghat, *Fluid Phase Equilib.*, **289**, Iss. 2: 129 (2010); doi:10.1016/j.fluid.2009.11.025
23. Mohammad Reza Talaghat, *Can. J. Chem. Eng.*, **90**, Iss. 1: 79 (2012);

doi:10.1002/cjce.20506
24. Mohammad Reza Talaghat, *J. Nat. Gas Sci. Eng.*, **18**: 7 (2014); doi:10.1016/j.jngse.2014.01.013
25. Yuhang Zhang, Wei Lu, Lina Cong, Jia Liu, Liqun Sun, Alain Mauger, Christian M. Julien, Haiming Xie, and Jun Liu, *J. Power Sources*, **420**: 63 (2019); doi:10.1016/j.jpowsour.2019.02.090
26. Koblan Wilfried Ebagninin, Adel Benchabane, and Karim Bekkour, *J. Colloid Interface Sci.*, **336**, Iss. 1: 360(2009); doi:10.1016/j.jcis.2009.03.014
27. Hind Ahmed and Ahmed Hashim, *Phys. Chem. Solid State*, **23**, Iss. 1: 67 (2022); doi:10.15330/pcss.23.1.67-71
28. F. de Brito Mota, J. F. Justo, and A. Fazzio, *Phys. Rev. B*, **58**, Iss. 13: 8323 (1998); doi:10.1103/PhysRevB.58.8323
29. G. Ziegler, J. Heinrich, and G. Wötting, *J. Mater. Sci.*, **22**, Iss. 9: 3041 (1987); doi:10.1007/BF01161167
30. V. Mohanavel and M. Ravichandran, *Silicon*, **14**, Iss. 4: 1381 (2022); doi:10.1007/s12633-020-00917-0
31. Christoph Loschen, Annapaola Migani, Stefan T. Bromley, Francesc Illas, and Konstantin M. Neyman, *Phys. Chem. Chem. Phys.*, **10**, Iss. 37: 5730 (2008); doi:10.1039/b805904g
32. Linhai Jiang, Mingguang Yao, Bo Liu, Quanjun Li, Ran Liu, Hang Lv, Shuangchen Lu, Chen Gong, Bo Zou, Tian Cui, Bingbing Liu, Guangzhi Hu, and Thomas Wegberg, *J. Phys. Chem. C*, **116**, Iss. 21: 11741 (2012); doi:10.1021/jp3015113
33. Areen A. Bani-Salameh, A. A. Ahmad, A. M. Alsaad, I. A. Qattan, and Ihsan A. Aljarrah, *Polymers*, **13**, Iss. 7: 1158 (2021); doi:10.3390/polym13071158
34. Ahmed Hashim, Majeed Ali Habeeb, Aseel Hadi, Bahaa H. Rabee, Mohammed Hashim Abbas, and Musaab Khudhur Mohammed, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 2: 281 (2023); doi:10.15407/nnn.21.02.281
35. Muhammad Nadeem, Ramsha Khan, Komal Afridi, Akhtar Nadhman, Sana Ullah, Sulaiman Faisal, Zia Ul Mabood, Christophe Hano, and Bilal Haider Abbasi, *Int. J. Nanomedicine*, **15**: 5951 (2020); doi:10.2147/IJN.S255784
36. Hind Ahmed and Ahmed Hashim, *Silicon*, **14**: 4907 (2022); https://doi.org/10.1007/s12633-021-01258-2
37. Hind Ahmed and Ahmed Hashim, *Trans. Electr. Electron. Mater.*, **23**: 237 (2022); https://doi.org/10.1007/s42341-021-00340-1
38. Hind Ahmed and Ahmed Hashim, *Silicon*, **14**: 7025 (2021); https://doi.org/10.1007/s12633-021-01465-x
39. Hind Ahmed and Ahmed Hashim, *Opt. Quant. Electron.*, **55**: 280 (2023); https://doi.org/10.1007/s11082-022-04528-4
40. Batool Mohammed, Hind Ahmed, and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 1: 113 (2023); https://doi.org/10.15407/nnn.21.01.113
41. Hind Ahmed and Ahmed Hashim, *Physics and Chemistry of Solid State*, **23**, Iss. 1: 67 (2022); doi:10.15330/pcss.23.1.67-71
42. Huda Bukheet Hassan, Hayder M. Abduljalil, and Ahmed Hashim, *Physics and Chemistry of Solid State*, **23**, Iss. 3: 454 (2022); doi:10.15330/pcss.23.3.454-460

43. Hind Ahmed and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **19**, Iss. 4: 841 (2021); https://doi.org/10.15407/nnn.19.04.841
44. Huda Bukheet Hassan, Hayder M. Abduljalil, and Ahmed Hashim, *AIP Conference Proceedings*, **2591**: 040008 (2023); https://doi.org/10.1063/5.0119838
45. Noor Al-Huda Al-Aaraji, Ahmed Hashim, Hayder M. Abduljalil, and Aseel Hadi, *Optical and Quantum Electronics*, **55**: Iss. 8: 743 (2023); https://doi.org/10.1007/s11082-023-05048-5
46. Huda Bukheet Hassan, Hayder M. Abduljalil, and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 2: 289 (2023); https://doi.org/10.15407/nnn.21.02.289
47. Hind Ahmed and Ahmed Hashim, *Silicon*, **15**: 83 (2023); https://doi.org/10.1007/s12633-022-01978-z
48. Fatema Sattar Jaber, Ahmed Hashim, and Hayder M. Abduljalil, *Silicon*, **15**: 71 (2023); https://doi.org/10.1007/s12633-022-02000-2
49. Hind Ahmed and Ahmed Hashim, *Optical and Quantum Electronics*, **54**: Article No. 403 (2022); https://doi.org/10.1007/s11082-022-03784-8
50. Hind Ahmed and Ahmed Hashim, *Silicon*, **14**: 4079 (2022); https://doi.org/10.1007/s12633-021-01186-1
51. Hind Ahmed and Ahmed Hashim, *Silicon*, **14**: 6637 (2022); https://doi.org/10.1007/s12633-021-01449-x
52. Hinde Ahmed and Ahmed Hashim, *Silicon*, **13**: 4331(2021); https://doi.org/10.1007/s12633-020-00723-8
53. Hind Ahmed and Ahmed Hashim, *Transactions on Electrical and Electronic Materials*, **22**: 335 (2021); https://doi.org/10.1007/s42341-020-00244-6
54. Noor Al-Huda Al-Aaraji, Ahmed Hashim, Aseel Hadi, and Hayder M. Abduljalil, *Silicon*, **14**: 10037 (2022); https://doi.org/10.1007/s12633-022-01730-7
55. Hind Ahmed and Ahmed Hashim, *Opt. Quant. Electron.*, **55**: 1 (2023). https://doi.org/10.1007/s11082-022-04273-8
56. Wissam Obeis Obaid and Ahmed Hashim, *Silicon*, **14**: 11199 (2022); https://doi.org/10.1007/s12633-022-01854-w
57. Ola Basim Fadil and Ahmed Hashim, *Silicon*, **14**: 9845 (2022); https://doi.org/10.1007/s12633-022-01728-1
58. Hind Ahmed and Ahmed Hashim, *Silicon*, **15**: 2339 (2023); https://doi.org/10.1007/s12633-022-02173-w
59. Huda Bukheet Hassan, Hayder M. Abduljalil, and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 941(2022); https://doi.org/10.15407/nnn.20.04.941
60. Haitham Ahmed Jawad and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 963 (2022); https://doi.org/10.15407/nnn.20.04.963
61. Ahmed Hashim, Ibrahim R. Agool, and Kadhim J. Kadhim, *Journal of Bionanoscience*, **12**, Iss. 5: 608 (2018); doi:10.1166/jbns.2018.1580
62. Angham Hazim, Ahmed Hashim, and Hayder M. Abduljalil, *International Journal of Emerging Trends in Engineering Research*, **7**, No. 8: 68 (2019); https://doi.org/10.30534/ijeter/2019/01782019
63. Angham Hazim, Hayder M. Abduljalil, and Ahmed Hashim, *International Journal of Emerging Trends in Engineering Research*, **7**, No. 8: 104 (2019);

https://doi.org/10.30534/ijeter/2019/04782019
64. Ola Basim Fadil and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 1029 (2022); https://doi.org/10.15407/nnn.20.04.1029
65. Wissam Obeis Obaid and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 1009 (2022); https://doi.org/10.15407/nnn.20.04.1009
66. Mohanad H. Meteab, Ahmed Hashim, and Bahaa H. Rabee, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 1: 199 (2023); https://doi.org/10.15407/nnn.21.01.199
67. Mohanad H. Meteab, Ahmed Hashim, and Bahaa H. Rabee, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 2: 451 (2023); https://doi.org/10.15407/nnn.21.02.451
68. Huda Bukheet Hassan, Ahmed Hashim, and Hayder M. Abduljalil, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 3: 815 (2022); https://doi.org/10.15407/nnn.20.03.815
69. Huda Bukheet Hassan, Ahmed Hashim, and Hayder M. Abduljalil, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 3: 821 (2022); https://doi.org/10.15407/nnn.20.03.821
70. Ghaith Ahmed and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 4: 867 (2023); https://doi.org/10.15407/nnn.21.04.867
71. Arshad Fadhil Kadhim and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 4: 877 (2023); https://doi.org/10.15407/nnn.21.04.877
72. Hind Ahmed and Ahmed Hashim, *International Journal of Scientific & Technology Research*, **8**, Iss. 11: 1014 (2019).
73. Batool Mohammed, Hind Ahmed, and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 1: 187 (2022); https://doi.org/10.15407/nnn.20.01.187
74. Huda Abdul Jalil Hussien, Raheem G. Kadhim, and Ahmed Hashim, *J. of Physics: Conf. Series*, **1818**: 012119 (2021); doi:10.1088/1742-6596/1818/1/012119
75. Huda Abdul Jalil Hussien, Raheem G. Kadhim, and Ahmed Hashim, *J. of Physics: Conf. Series*, **1818**: 012186 (2021); doi:10.1088/1742-6596/1818/1/012186
76. Huda Abdul Jalil Hussien, Raheem G. Kadhim, and Ahmed Hashim, *J. of Physics: Conf. Series*, **1818**: 012187 (2021); doi:10.1088/1742-6596/1818/1/012187
77. Abeer Ghalib Hadi, Zainab Al-Ramadhan, and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **19**, Iss. 4: 865 (2021); https://doi.org/10.15407/nnn.19.04.865
78. Ahmed Hashim and Zinah Sattar Hamad, *Nanosistemi, Nanomateriali, Nanotehnologii*, **19**, Iss. 4: 893 (2021); https://doi.org/10.15407/nnn.19.04.893
79. K. H. H. Al-Attiyah, A. Hashim, and S. F. Obaid, *Journal of Bionanoscience*, **12**: 200 (2018); doi:10.1166/jbns.2018.1526
80. A. S. Shareef, F. Lafta R., A. Hadi, and A. Hashim, *International Journal of Scientific & Technology Research*, **8**, Iss. 11: 1041 (2019).
81. Aseel Hadi, Ahmed Hashim Ah-yasari, and Dalal Hassan, *Bulletin of Electrical Engineering and Informatics*, **9**, No. 1: 83 (2020);

doi:10.11591/eei.v9i1.1323
82. Hind Ahmed and Ahmed Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 951 (2022); https://doi.org/10.15407/nnn.20.04.951
83. Farhan Lafta Rashid, Aseel Hadi, Ammar Ali Abid, and Ahmed Hashim, *International Journal of Advances in Applied Sciences*, **8**, No. 2: 154 (2019); doi:10.11591/ijaas.v8i2.pp154-156
84. Maithem Hussein Rasheed, Ahmed Hashim, and Farhan Lafta Rashid, *Nanosistemi, Nanomateriali, Nanotehnologii*, **19**, Iss. 2: 374 (2021); https://doi.org/10.15407/nnn.19.02.347
85. A. Hashim, F. L. Rashid, N. AH. Al-Aaraji, and B. H. Rabee, *East European Journal of Physics*, **1**: 173 (2023); doi:10.26565/2312-4334-2023-1-21
86. F. L. Rashid, A. Hashim, N. AH. Al-Aaraji, and A. Hadi, *East European Journal of Physics*, **1**: 177 (2023); doi:10.26565/2312-4334-2023-1-22
87. F. L. Rashid, A. Hashim, M. H. Abbas, and A. Hadi, *East European Journal of Physics*, **1**: 181 (2023); doi:10.26565/2312-4334-2023-1-23
88. A. Hashim, F. L. Rashid, M. H. Abbas, and B. H. Rabee, *East European Journal of Physics*, **1**: 185 (2023); doi:10.26565/2312-4334-2023-1-24