Brainwave: A Multidisciplinary Journal (ISSN: 2582-659X), Vol. 1, No. 2, December 2020, pp. 109-117, © Brainware University

Insight into Nanotechnology Enabled Intervention to Mitigate COVID-19 Pandemic

Anal Mandal[1*]
2001analmandal@gmail.com

Sriparna De[2]
sd.ah@brainwareuniversity.ac.in

[1] *Student, Dept. of Allied Health Sciences, Brainware University*
[2] *Assistant Professor, Dept. of Allied Health Sciences, Brainware University*
**Corresponding Author*

Abstract

The current millennium has perceived the emergence of highly contagious strains of Coronavirus 2019 (COVID-19), as a prime tenet of mortality, morbidity and economic crisis globally. The prime causative agent of COVID 19 is highly contagious severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), At present the genetic diversity of corona viruses encounter a technological appeal for the development of diagnostics and therapeutics strategies. Stratagems need to be revealed to amplify testing capacities, to cultivate effective theranostic prevention, and to develop safe vaccination that provide prolonged immunity. By virtue of versatile physicochemical properties of nanoparticles (NPs) used in numerous applications such as biosensing, drug delivery, imaging, and antimicrobial treatment to cope with pandemics. The interplay of nanostructured materials with microorganisms is refashioned by offering leverages in both diagnostic and therapeutic applications. Miniaturization of nanoparticles which can meticulously mimic and intermingle with the morphological alike virus surface spike proteins. Highly sensitive detection tool to counter low virus concentration and real time shields can efficiently offer tactical roadmaps towards the inevitable breakthrough in various disease therapeutics. Herein we envision the concurrent execution of amalgamation of nanoscience and nanotechnology could symbolize new avenues for disruption of virion construction and to fight against the viral life span. We feature current as well as ongoing nanotechnology enabledtherapeutic and prophylactic roadmaps to combat against this pandemic and zoning the pivotal avenues for nanoscientific community to nurture future anti-viral research.

Key words: Nanostructured material, Nanotechnology, Cytokines strom, Nanobiosensor,Contagious, SARS-CoV-2, Virion,

Introduction

The entire mankind on our planet is now endangered by an interminable nightmare by invisible enemy which is hitherto mysterious to mankind and imposing serious illness and infections. As countries introduce unprecedented measures to stem the spread of COVID-19, one of the most alarming inferences from this infectious-disease modelling is that there is no clear exit stratagem. This pandemic is truncated as COVID-19 (Coronavirus Disease 2019), originated in Wuhan, Hubei province, in 31 December, 2019 and rapidly spread all over the world[1,2].This virus appeared as a novel human pathogen that causes severe acute respiratory syndrome (SARS). According to the World Health Organization (WHO) bulletin, there is continual emergence of viral diseases, which causes serious concern to public health and medical fraternity. The stereotypical approach against a viral pandemic needs multifaceted scientific methodology [3,4].Diagnostics viral detection through a biosensor technology is the prime requirement which can mitigate the spread and breakage of viral transmission chain by isolating infected person. Specifically, large scale of testing with higher efficacy and accuracy is required is to monitor a broad pictograph of viral spread. Besides that, the therapeutic strategy development in terms of nanocarrier and nanodrug formulation is yet to be achieved its pinnacle, perquisite to handle morbidity and mortality due to viral contamination.Dan Barouch, director of the Center for Virology and Vaccine Research at Beth Israel Deaconess Medical Center quoted “Everything from basic science to clinical science is progressing at a pace faster than ever before—and very appropriately, given the grave nature of the current global crisis,” the bulletin of WHO reveals least 70 COVID-19 vaccines are in developmental stage [5].

Subsequent clinical trials have already been initiated and coming with satisfactory interpretations. Recently, cell membranes mimicking nanodecoys including liposomal formulations, reconstituted lipoproteins, an interesting choice to scavenge the pathogens. protein-based vaccines such as recombinant-protein, viral vector, attenuated is also explored to tackle this SARS-CoV-2. For instance, the brainchild of 'nano immunity by design' entrust on the rational blueprint of distinctive physicochemical properties and anticipated for fine-tuning their prospective on the immunomodulation system. Adopting this proposed advancement and technological know-how, this short review portrays emblematic perception of nanomaterials and its intervention to combat against viruses from Coronaviridae family causing prevailing health concerns in future [6].

Nanoparticles inhibit viral infection

It is well-known that virostatic and virucidal, two types of antiviral analytes categorized on the basis of the counteracting synergism against a particular virus, impeding viral replication and proliferation [7].Nevertheless, many of the effective antiviral agents are showing toxic response. To address this issue research on the antiviral characteristics of nanomaterials is still lies in its embryonic state. The main curiosity in these systems denigrations indeed in their low toxicityand fertile virus inhibition mechanisms. Nanoscale systems will be inspired by merging virostatic with virucidal inactivation processes [8].In the context of nanomedicine, many nanomaterials have been explored, wherein nonpharmaceutical denotes to broad spectrum of nanomaterial with therapeutic potential, for example, dendrimers,liposomes, micelles and nanocapsules [9].Owing to fascinating inhibitory mechanism of MONPs through reactive oxygen species generation and blocking the S spike protein of the micro-organisms interplay with the cellular ACE2 receptor. Herein we highlight the various nano-cargo system and their potential efficiency towards drug delivery and therapeutic applications.

Gold nanoparticle

Gold nanoparticles have considerable attention and offering effective antiviral activity against viruses. Sialic acid-functionalized AuNPs showed resistance against influenza virus infection, relatively superior than conventional synthetic drugs such as zanamivir and oseltamivir [10,11].Concurrently, AuNPs improved the immune response by decreasing the mRNA expression of interleukin (IL)-1 IL-6, tumor necrosis factor (TNF)-α, IFN-γ and inducible nitric oxide synthase which thereby could be a promising alternative and participating noticeably in antiviral therapeutics [12]. Furthermore, gold nanoclusters (AuNCs) restricted and blocked viral entry site of respiratory syndrome virus, precisely histidine-functionalized AuNCs illustrate mitigate the proliferation of pseudorabies virus (PRV) [13,14].

Silver nanoparticle

Additionally, owing to the fascinating physicochemical and biological properties of silver nanoparticles (AgNPs), are adopted as antiviral, antibacterial, anti-inflammatory, anti-angiogenesis, antiplatelet, antifungal and anticancer applications. Fungi-Mediated synthesis of AgNPs minimized the viral load against HSV-1/2 and with human parainfluenza virus type 3. [15]. AgNPs exposed antiviral and defensive effects against H3N2 influenza virus [16]. Silver nanocluster silica composite sputtered coating used for the FFP3 face mask which diminished the titer of SARS-CoV-2 to zero [17]. silver NPs with aqueous leave and fruit extracts from *Ricinuscommunis* inhibited Coxsackievirus [18]. silver NPs(biosynthesized) showed anti-dengue activity using algae (*Centrocerasclavulatum*), plant (*Bruguieracylindrical*), and seed (*Moringaoleifera*) extract concentrations of 12.5–50, 30, and

20 µg/ml [19,20,21]. Silver NPs helps to block the herpesvirus entry into the host cell [22,23]. Silver NPs (12–28 nm) with leaf extracts from *Rhizophoralamarckii* also inhibited HIV-1 [24]. silver NPs (50 nm) have 92% antiviral activity against hepatitis B [25].

Other metal nanoparticles

Selenium NPs bind with the oseltamivir inhibited enterovirus activity by abating the production of Reactive oxygen species in human astrocytoma cells [26]. It shows affected treatment of influenza with ribavirin (RBV) [27]. It shows effective treatment of Dengue Virus [28]. Whereas zinc nanoparticles inhibit the viral DNA polymerase activity of Herpes Simplex Virus [29]. zinc oxide at a low concentration of 2.5 pg/ml acts as anti-chikungunya by reducing the levels of viral RNA transcripts within 24 h of infection as revealed by RT-PCR [30]. Copper nanoparticles produce reactive oxygen species to inactivate the Herpes Simplex Virus by oxidation of viral proteins or degradation of the viral genome [31]. Copper NPs help to block the entry and attachment stages of hepatitis infection [32]. Copper oxide NPs with leaf exacts of *Tridaxprocumbens* showed larvicidal activity against the chikungunya vector at a dose of 4.209 mg/L [33]. It has the capability to reduce the antiviral activity of Dengue Virus [34]. Gallium NPs (bind with glucan) inhibited HIV and suppress the co-infection of HIV and tuberculosis [35]. Iron oxide NP inhibits the H1N1 influenza (50%) at a concentration of 1.1 pg [36]. Titanium dioxideNPsdecreased the cell viability of murine norovirus (MNV) [37]. Tungsten carbide NPshave antiviral activity against norovirus and it caused a four-log reduction of murine norovirus within 15 min [38]. It assists in the reduction of poliovirus infectivity (3.5-log) within 15 min [38].

Carbon nanoparticle

Carbon Dots derived from Benzoxazine monomer inhibited the flavivirus infectivity [39]. Cdots bond with an amine, inhibited the entry of HSV-1 into host cells [40]. Carbon quantum dots (CQDs) derived from hydrothermal carbonization of citric acid, inhibited the entry and replication of HCoV-229E [41]. GO inhibits the replication of HIV [42]. GO loaded with Hypericin protected against novel duck reovirus (NDRV) [43]. GO with curcumin inhibits the Respiratory syncytial virus [44]. It acts as antiviral agents of hand, foot and mouth disease [45].

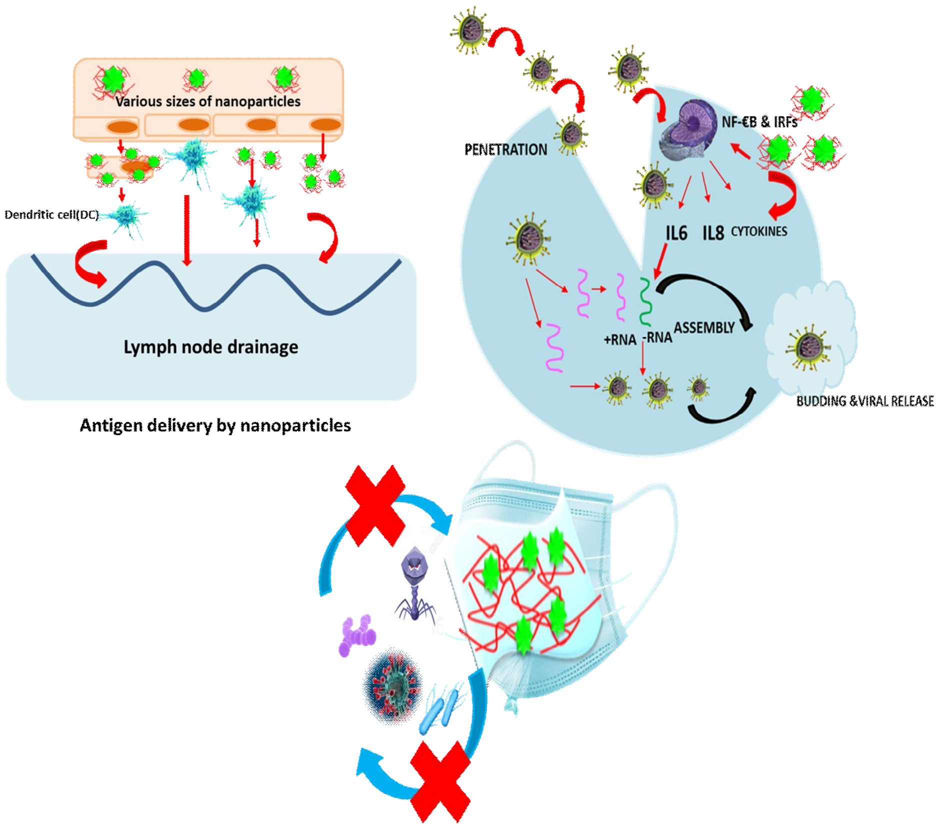

Fig: 1 Schematic representation of Nanosystems based antiviral mechanistic approach

Reusable and Recyclable Mask

Disposable surgical masks or respirators can inhibit respiration droplets containing viruses inflowing through the lungs, assisting to reduce the possibility of getting infected, alongside maintaining proper hygiene practice. However, the conventional masks are having some limitation including surface hydrophobicity, reusability and recyclability. To overcome such constrictions emerging nanostructured materials and polymeric fibers, Fluorinated polymer,metal nanowires and graphene have been explored as superhydrophobic coatings. Superhydrophobic surface coatings on the N95 respirators can be achieved by laser-induced graphene material, is adaptable, scalable and cost-effective as compared to commercially available precursors, such as polyimide, SPEEK, and Bakelite. Hong Zhong et. al developed dual-mode laser-induced forward transfer process for accumulating graphene onto commercial surgical mask coating application. [46]. The decontamination stratagem is enriched with the usage of nanostructured and layered graphene coatings, with a static contact angle of over 140° achieved, wherein enhanced superhydrophobicity leads to least adherence of virus droplets onto mask surface. Additionally, the solar illumination induces the surface sterilization by prompt ascent the surface temperature of about 80^{o}C [47]. Meanwhile the plasmonic photothermal and superhydrophobic coating on N95 respirators, offering profound protection than existing personal protection equipment. The coating of the silver nanoparticles deliver extra shielding effect through silver ion's decontamination toward microbes. These synergistic landscapes of the nanostructured composite coatings can enthuse future scientific community to miniaturize advanced personal protection equipment to fight against COVID-19 pandemic.

Application of biosensors to screen SARS-CoV-2

It is alleged that the high transmissibility and contagious nature of COVID-19 is coupled to its high viral loads in the upper respiratory tract and the fact that many individuals endure asymptomatic, shedding and spreading the virus. Critical nanotechnological interventions to combat against pandemics include the cessation of pathogen spreading, accomplish suitable diagnostic tool, and proper immunization. For instance, nanodiagnostics scheme lies on the specific interaction between nanoparticles and target analyte of interest to yield a measurable signal output; catering the detection of biomarkers or pathogens at its early stages.Nanobiosensors are appreciated substitute to conventional diagnostic tool that offer assessment of single molecules with high sensitivity, specificity, precision characteristics for clinical and environmental analyses. Au-Np anchored Nano-platforms and FET sensor (modified with graphene sheets) that customs a specific antibody against SARS-CoV-2 spike protein was testified to detect SARS-CoV-2 in culture medium. The sensor exhibits limit of detection LOD of 1.6 × 101 pfu/mL) in good contrast to real clinical samples (LOD: 2.42 × 102 copies/mL) [48].Gold NPs studded DNA strands on electrode surface were customized to sense in-situ amplified CTV (RPA assay for amplification of the P20 gene) using electrochemical impedance spectroscopy (EIS) analysis wherein the DNA sensor displays very low LOD of 1000 fg/μL [49].Recently Paper/nanomaterial-modified sensing techniques, particularly, NP-based lateral-flow devices that are perceived with the naked eye or control through a smartphone are the furthermost conveyed testing daises for the screening of COVID-19-related biomarkers. Extensive research has also validated solid-phase isothermal recombinase polymerase amplification (RPA) strategies for the detection of Citrus tristeza virus (CTV) for plant disease diagnostics [50].

Implication of nanotechnology to mitigate the cytokines storm

Cytokines are a group of signaling molecules that mediate and govern our immunological system. COVID-19 triggers cytokine storm within the body, defined as cytokine release syndrome (CRS), which emanate from an excessive immune response. This inflammatory cytokine storm is one of the pivotal roots of the acute respiratory distress syndrome (ARDS) aiding multiple-organ failure depicting the foremost causes of death in critical patients. Notably, extensive current research on drug trial on Interleukin (IL)-6 that block its receptor site (Tocilizumab, an anti-IL-6 receptor antibody, and Sarilumab) or IL-6 itself (Siltuximab). On account of the salient feature of macrophages in COVID-19, ACE2-expressing CD68+CD169+ macrophages comprising SARS-CoV-2 nucleoprotein antigen exhibits an amplified discharge of IL-6 in infected lymphatic system [51].The tissues infected by SARS-CoV-2 also deployed an upregulated expression of Fas, signifying the involvement of CD169+ macrophages in several pathogenesis viral spreading, anomalous inflammation, and lymphocyte apoptosis. Enlarged alveolar exudate caused by prolonged neutrophil and monocyte infiltrate in lung capillaries with fibrin deposition has also been monitored in biopsy slides of infected patients. The state of art of *Nanomedicine* could be highly promising in this plethora by inducing specificity/efficiency of immunosuppressant delivery to target immune cells with subsequent minimization of drug overdose and its possible side-effects[52].The distinct architecture of Nanotool design can substantially circumvent the immune system, thereby tuned the surface charge and provides favourable room for drug encapsulation or loading. Carbon based porous nanostructured particularly graphene has remarkable potential to scavenge the CRS from serum by extracorporeal perfusion technique. Additionally, Hierarchical porus carbon nanomatrix have displayed effective adsorption of several cytokines, including IL-6 and TNF-α. Impressively through nanotechnology and nanomedicine we can envision therapeutic modalities and target specific immune subpopulations by utilizing as a fascinating immunomodulatory platform[53].

Conclusion & Rethinking the future traits

To mitigate COVID-19 global emergency which evoke an unprecedented threat and enact serious negative waves on the societies including the healthcare systems, nanotechnological intervention is intrinsically furnish advanced tools and schematic methodology for bottomless understanding of pathophysiology of various viral diseases. The unique architecture of nano-tailored sensing platform, various nanocarrier system like nanotraps, nanorobots, nanobubbles, nanoribbons, and nanodiamonds are paving their way in the diagnosis, prevention, and therapeutics of viral infections. Nano Traps are potentially fashioned to scavenge the targeted infectious virion and viral proteins through hydrophobic and electrostatic interactions. Surprisingly miniaturized nanorobot comprised of polymeric/biopolymeric material biomimetic materials capable of prompt pathogens detection, genome editing and therapeutics delivery vehicle could be noteworthy for early detection of pathogens and eradicating them. Future endeavour can be triggered to design nanofibers, nanodiamonds, nanobubbles as nanotraps in site-specific delivery of numerous drugs providing broad spectrum of theranostic tools for diseases diagnosis and associated comorbidities in a heterogeneous population. Further research to upgrade immune response and usage of nanomaterials as adjuvant to antiviral vaccines have been encouraging in the prevention and control of viral infections [47].

Acknowledgement

The authors acknowledge Dr. Sriparna De for their esteemed edits, suggestions and contributions to this manuscript**.** Also, authors are thankful to all faculty members of department of Allied Health Sciences for their constant support and motivation.

Conflict of interest

The authors declare that they have no conflicts of interest concerning this article.

References

1. Lukashev, A. N.; Zamyatnin, A. A. Viral Vectors for Gene Therapy:Current State and Clinical Perspectives. Biochemistry (Moscow) 201,

2.Vincent, M.; de Lázaro, I.; Kostarelos, K. Graphene Materials as 2D Non-Viral Gene Transfer Vector Platforms. Gene Ther. 2017, 24, 123−132.

3. Watkins, K. Emerging Infectious Diseases: A Review. Curr. Emerg. Hosp. Med. Rep. 2018, 6, 86−93.

4.WHO report-98, Johns Hopkins University. www.coronavirus.jhu.edu/map.html (accessed 2020-05-19).

5.COVID-19 vaccines move toward clinic;APRIL 20, 2020 | CEN.ACS.ORG,Chemistry news from the week.

6.Toward Nanotechnology-Enabled Approaches against the COVID-19 Pandemic, Carsten Weiss,*,# Marie Carriere,*,# Laura Fusco, ACS Nano, https://dx.doi.org/10.1021/acsnano.0c03697]

7.Yasmin Abo-zeid1,2 | Gareth R. Williams2 the potential anti-infective applications of metal oxide nanoparticles: A systematic review; WIREs NanomedNanobiotechnol. 2019; e1592.]

8. Parboosing R, Maguire GE, Govender P, et al.Nanotechnology and the treatment of HIV infection. Viruses 2012; 4: 488–520.,

9. Bawa R. Nanopharmaceuticals:nanopharmaceuticals. Eur J Nanomed 2010; 3:34–40.]

10. Wen, W.H.; Lin, M.; Su, C.Y.; Wang, S.Y.; Cheng, Y.S.E.; Fang, J.M.; Wong, C.H. Synergistic effect ofzanamivir-porphyrin conjugates on inhibition of neuraminidase and inactivation of influenza virus. J. Med.Chem. 2009, 52, 4903–4910. [CrossRef]

11.Papp, I.; Sieben, C.; Ludwig, K.; Roskamp, M.; Böttcher, C.; Schlecht, S.; Herrmann, A.; Haag, R. Inhibitionof influenza virus infection by multivalent sialic-acid- functionalized gold nanoparticles. Small 2010, 6,2900–2906. [CrossRef] [PubMed]

12.Dkhil, M.A.; Bauomy, A.A.; Diab, M.S.; Al-Quraishy, S. Antioxidant and hepatoprotective role of goldnanoparticles against murine hepatic schistosomiasis. Int. J. Nanomed. 2015, 10, 7467. [CrossRef]

13. Bai, Y.; Zhou, Y.; Liu, H.; Fang, L.; Liang, J.; Xiao, S. Glutathione-stabilized fluorescent gold nanoclustersvary in their influences on the proliferation of pseudorabies virus and porcine reproductive and respiratorysyndrome virus. ACS Appl. Nano Mater. 2018, 1, 969–976. [CrossRef]

14.Feng, C.; Fang, P.; Zhou, Y.; Liu, L.; Fang, L.; Xiao, S.; Liang, J. Different Effects of His-Au NCs and MES-AuNCs on the propagation of pseudorabies virus. Glob. Chall. 2018, 2, 1800030. [CrossRef] [PubMed]

15. Gaikwad, S.; Ingle, A.; Gade, A.; Rai, M.; Falanga, A.; Incoronato, N.; Russo, L.; Galdiero, S.; Galdiero, M.Antiviral activity of mycosynthesized silver nanoparticles against herpes simplex virus and humanparainfluenza virus type 3. Int. J. Nanomed. 2013, 8, 4303–4314. [CrossRef]

16. Xiang, D.; Zheng, C.; Zheng, Y.; Li, X.; Yin, J.; O' Conner, M.; Marappan, M.; Miao, Y.; Xiang, B.; Duan, W.;et al. Inhibition of A/Human/Hubei/3/2005 (H3N2) influenza virus infection by silver nanoparticles in vitroand in vivo. Int. J. Nanomed. 2013, 8, 4103. [CrossRef]

17. Balagna C, Perero S, Percivalle E, Nepita EV, Ferraris M (2020)Virucidal effect against Coronavirus SARS-CoV-2 of a silvernanocluster/silica composite sputtered coating. Open Ceram 1:100006

18. Salem BAN et al (2012) Plant-derived nanoparticles enhance an-tiviral activity against coxsakievirus B3 by acting on virus parti-cles and vero cells. Digest J NanomaterBiostruct 7(2):737–744

19. Murugan K, Aruna P, Panneerselvam C, Madhiyazhagan P,Paulpandi M, Subramaniam J, Rajaganesh R, Wei H, AlsalhiMS, Devanesan S, Nicoletti M, Syuhei B, Canale A, Benelli G(2016) Fighting arboviral diseases: low toxicity on mammalian cells, dengue growth inhibition (in vitro), and mosquitocidal activity of Centroceras clavulatum-synthesized silver nanoparticles.Parasitol Res 115(2):651–662

20. Murugan K, Dinesh D, Paulpandi M, Althbyani ADM,Subramaniam J, Madhiyazhagan P, Wang L, Suresh U, KumarPM, Mohan J, Rajaganesh R, Wei H, Kalimuthu K, ParajuleeMN, Mehlhorn H, Benelli G (2015) Nanoparticles in the fightagainst mosquito-borne diseases: bioactivity of Bruguieracylindrica-synthesized nanoparticles against dengue virus DEN-2 (in vitro) and its mosquito vector Aedes aegypti (Diptera:Culicidae). Parasitol Res 114(12):4349–4361

21. Sujitha V, Murugan K, Paulpandi M, Panneerselvam C, Suresh U,Roni M, Nicoletti M, Higuchi A, Madhiyazhagan P,Subramaniam J, Dinesh D, Vadivalagan C, Chandramohan B,Alarfaj AA, Munusamy MA, Barnard DR, Benelli G (2015)Green-synthesized silver nanoparticles as a novel control toolagainst dengue virus (DEN-2) and its primary vector Aedesaegypti. Parasitol Res 114(9):3315–3325

22 . Akbarzadeh A, Kafshdooz L, Razban Z, DastranjTbrizi A,Rasoulpour S, Khalilov R, Kavetskyy T, Saghfi S, NasibovaAN, Kaamyabi S, Kafshdooz T (2018) An overview applicationof silver nanoparticles in inhibition of herpes simplex virus. ArtifCells NanomedBiotechnol 46(2):263–267

23. Etemadzade M, Ghamarypour A, Zabihollahi R, shabbak G,Shirazi M, Sahebjamee H, Vaziri AZ, Assadi A, Ardestani MS,Shandiz SAS, Aghasadeghi MR (2016) Synthesis and evaluationof antiviral activities of novel sonochemical silver nanorodsagainst HIV and HSV viruses. Asian Pacif J Trop Dis 6(11):854–858

24.Kumar SD, Singaravelu G, Ajithkumar S, Murugan K, NicolettiM, Benelli G (2017) Mangrove-mediated green synthesis of silvernanoparticles with high HIV-1 reverse transcriptase inhibitory po-tential. J ClustSci 28(1):359–367

25. Lu L, Sun RW, Chen R, Hui CK, Ho CM, Luk JM, Lau GK, CheCM (2008) Silver nanoparticles inhibit hepatitis B virus replication. AntivirTher 13(2):253–262

26. Zhong J, Xia Y, Hua L, Liu X, Xiao M, Xu T, Zhu B, Cao H(2019) Functionalized selenium nanoparticles enhance the anti-EV71 activity of oseltamivir in human astrocytoma cell model.Artif Cells NanomedBiotechnol 47(1):3485–3491

27. Lin Z, Li Y, Gong G, Xia Y, Wang C, Chen Y, Hua L, Zhong J,Tang Y, Liu X, Zhu B (2018) Restriction of H1N1 influenza virusinfection by selenium nanoparticles loaded with ribavirin viaresisting caspase-3 apoptotic pathway. Int J Nanomedicine 13:5787–5797

28. Abinaya M, Vaseeharan B, Rekha R, Shanthini S, GovindarajanM, Alharbi NS, Kadaikunnan S, Khaled JM, al-Anbr MN (2019)Microbial exopolymer-capped selenium nanowires–towards newantibacterial, antibiofilm and arbovirus vector larvicides? JPhotochemPhotobiol B Biol 192:55–67

29. Tavakoli A, Ataei-Pirkooh A, MM Sadeghi G, Bokharaei-SalimF, Sahrapour P, Kiani SJ, Moghoofei M, Farahmand M,Javanmard D, Monavari SH (2018) Polyethylene glycol-coatedzinc oxide nanoparticle: an efficient nanoweapon to fight againstherpes simplex virus type 1. Nanomedicine 13(21):2675–2690

30.Kumar R, Sahoo G, Pandey K, Nayak MK, Topno R, Rabidas V,Das P (2018) Virostatic potential of zinc oxide (ZnO) nanoparti-cles on capsid protein of cytoplasmic side of chikungunya virus.Int J Infect Dis 73:368

31. Tavakoli A, Hashemzadeh MS (2020) Inhibition of herpes sim-plex virus type 1 by copper oxide nanoparticles. J Virol Methods275:113688

32. Hang X, Peng H, Song H, Qi Z, Miao X, Xu W (2015) Antiviralactivity of cuprous oxide nanoparticles against hepatitis C virusin vitro. J Virol Methods 222:150–157

33. Selvan SM et al (2018) Green synthesis of copper oxide nanopar-ticles and mosquito larvicidal activity against dengue, Zika andchikungunya causing vector Aedes aegypti. IET Nanobiotechnol12(8):1042–1046

34. Sharon EA, Velayutham K, Ramanibai R (2018) Biosynthesis ofcopper nanoparticles using Artocarpus heterophyllus against den-gue vector Aedes aegypti. Int J Life SciScienti Res eISSN2455(1716):1716

35. Choi S-r, Britigan BE, Narayanasamy P (2017) Ga (III) nanopar-ticles inhibit growth of both Mycobacterium tuberculosis and HIVand release of interleukin-6 (IL-6) and IL-8 in coinfected macro-phages. Antimicrob Agents Chemother 61(4):e02505–e02516

36. Kumar R, Nayak M, Sahoo GC, Pandey K, Sarkar MC, Ansari Y,Das VNR, Topno RK, Bhawna, Madhukar M, Das P (2019) Ironoxide nanoparticles based antiviral activity of H1N1 influenza Avirus. J Infect Chemother 25(5):325–329

37. Agnihothram S, Mullis L, Townsend TA, Watanabe F, Mustafa T,Biris A, Manjanatha MG, Azevedo MP, United States Food andDrug Administration, National Center for Toxicological Research2016) Titanium dioxide nanoparticles evoke proinflammatory re-sponse during Murine norovirus infection despite having minimaleffects on virus replication. Int J Nanotechnol Med Eng 1(3):63–73

38. Pfaff F, Glück B, Hoyer T, Rohländer D, Sauerbrei A, Zell R(2019) Tungsten carbide nanoparticles show a broad-spectrumvirucidal activity against enveloped and nonenveloped model vi-ruses using a guideline-standardized in vitro test. Lett ApplMicrobiol 69(4):302–309

39. Huang, S.; Gu, J.; Ye, J.; Fang, B.; Wan, S.; Wang, C.; Ashraf, U.; Li, Q.; Wang, X.; Shao, L.; et al. Benzoxazinemonomer derived carbon dots as a broad-spectrum agent to block viral infectivity. J. Colloid Interface Sci.2019, 542, 198–206. [CrossRef]

40. Barras, A.; Pagneux, Q.; Sane, F.; Wang, Q.; Boukherroub, R.; Hober, D.; Szunerits, S. High efficiency offunctional carbon nanodots as entry inhibitors of herpes simplex virus type 1. ACS Appl. Mater. Interfaces2016, 8, 9004–9013. [CrossRef]

41. Łoczechin, A.; Séron, K.; Barras, A.; Giovanelli, E.; Belouzard, S.; Chen, Y.T.; Metzler-Nolte, N.;Boukherroub, R.; Dubuisson, J.; Szunerits, S. Functional carbon quantum dots as medical countermeasuresto human coronavirus. ACS Appl. Mater. Interfaces 2019, 11, 42964–42974. [CrossRef]

42. Iannazzo, D.; Pistone, A.; Salamò, M.; Galvagno, S.; Romeo, R.; Giofré, S.V.; Branca, C.; Visalli, G.; Di Pietro, A.Graphene quantum dots for cancer targeted drug delivery. Int. J. Pharm. 2017, 518, 185–192. [CrossRef]

43. . Du, X.; Xiao, R.; Fu, H.; Yuan, Z.; Zhang, W.; Yin, L.; He, C.; Li, C.; Zhou, J.; Liu, G.; et al. Hypericin-loadedgraphene oxide protects ducks against a novel duck reovirus. Mater. Sci. Eng. C 2019, 105, 110052. [CrossRef]

44. Yang, X.X.; Li, C.M.; Li, Y.F.; Wang, J.; Huang, C.Z. Synergistic antiviral effect of curcumin functionalizedgraphene oxide against respiratory syncytial virus infection. Nanoscale 2017, 9, 16086–16092. [CrossRef]

45. Song, Z.; Wang, X.; Zhu, G.; Nian, Q.; Zhou, H.; Yang, D.; Qin, C.; Tang, R. Virus capture and destruction bylabel-free graphene oxide for detection and disinfection applications. Small 2015, 11, 1171–1176. [CrossRef]

46. Hong Zhong, Zhaoran Zhu, Peng You, Jing Lin, Chi Fai Cheung, Vivien L. Lu, Feng Yan,Ching-Yuen Chan, and Guijun Li*Plasmonic and Superhydrophobic Self-Decontaminating N95 Respiratorshttps://dx.doi.org/10.1021/acsnano.0c03504

47. Hong Zhong, Zhaoran Zhu, Jing Lin, Chi Fai Cheung, Vivien L. Lu, Feng Yan, Ching-Yuen Chan,andGuijun Li*Reusable and Recyclable Graphene Mask with Outstanding SuperhydrophobicandPhotothermal Performanceshttps://dx.doi.org/10.1021/acsnano.0c02250

48. Seo, G.; Lee, G.; Kim, M. J.; Baek, S.-H.; Choi, M.; Ku, K. B.;Lee, C.-S.; Jun, S.; Park, D.; Kim, H. G.; Kim, S.-J.; Lee, J.-O.; Kim, B.T.; Park, E. C.; Kim, S. I. Rapid Detection of COVID-19 CausativeVirus (SARS-CoV-2) in Human Nasopharyngeal Swab SpecimensUsing Field-Effect Transistor-Based Biosensor. ACS Nano 2020, 14,5135−5142

49. Khater, M.; Escosura-Muñiz, A. d. l.; Altet, L.; Merkoçi, A. InSitu Plant Virus Nucleic Acid Isothermal Amplification Detection on Gold Nanoparticle-Modified Electrodes. Anal. Chem. 2019, 91, 4790−4796.

50. Can nanotechnology help in the fight againstCOVID-19? Gabriela Palestino , Ileana García-Silva , Omar González-Ortega & SergioRosales-Mendoza, EXPERT REVIEW OF ANTI-INFECTIVE THERAPY2020, VOL. 18, NO. 9, 849–864

51. Chen, Y.; Feng, Z.; Diao, B.; Wang, R.; Wang, G.; Wang, C.;Tan, Y.; Liu, L.; Wang, C.; Liu, Y.; Liu, Y.; Yuan, Z.; Ren, L.; Wu, Y. TheNovel Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) Directly Decimates Human Spleens and Lymph Nodes. medRxiv2020, DOI: 10.1101/2020.03.27.20045427.

52.Yang, Y.; Shen, C.; Li, J.; Yuan, J.; Wei, J.; Huang, F.; Wang, F.; Li, G.; Li, Y.; Xing, L.; Peng, L.; Yang, M.; Cao, M.; Zheng, H.; Wu, W.;Zou, R.; Li, D.; Xu, Z.; Wang, H.; Zhang, M.; et al. Exuberant Elevationof IP-10, MCP-3 and IL-1ra During SARS-CoV-2 Infection IsAssociated with Disease Severity and Fatal Outcome. medRxiv 2020,DOI: 10.1101/2020.03.02.20029975.

53.Chen, Y.; Feng, Z.; Diao, B.; Wang, R.; Wang, G.; Wang, C.; Tan, Y.; Liu, L.; Wang, C.; Liu, Y.; Liu, Y.; Yuan, Z.; Ren, L.; Wu, Y. The Novel Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) Directly Decimates Human Spleens and Lymph Nodes. medRxiv2020, DOI: 10.1101/2020.03.27.20045427.