An Acad Bras Cienc (2020) 92(4): e20200718 DOI 10.1590/0001-3765202020200718
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

HEALTH SCIENCES

Promising Nanostructured Materials against Enveloped Virus

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Abstract: The development of self-disinfectant devices is highly needed to prevent and control infections, mainly caused by virus. In the past years, coronaviruses have been a threat to humanity, causing severe epidemics of respiratory infections such as severe acute respiratory syndrome (SARS), in 2003, and Middle East respiratory syndrome (MERS) in 2012, and presently the SARS-CoV2 is causing the COVID-19 pandemic. Previous studies have demonstrated that surface contamination play a significant role in the spreading of viruses. These studies demonstrated that the production of highly reactive species by copper alloys contributes to rapid elimination of viruses. Nanostructured materials such as semiconductors TiO_2, Co_3O_4 CuO, NiO, and TiO_2, and silver nanoparticles can decrease the virus viability on the surfaces when associated with polymers and textiles, especially in conditions of light exposure. In addition, graphene oxide is rising as a promising material for inactivation of viruses due to its capacity of destroying the viral envelope and capsid. The virucidal property of these materials can be enhanced by increasing their functionalization with photosensitizers. The present mini-review brings subsidies for the development of new advanced self-disinfectant materials that can be used in the manufacture of gloves, masks, and a variety of other devices.

Key words: Enveloped virus, SARS-CoV-2, nanostructured materials, semiconductors, metallic nanoparticles, self-disinfecting materials.

INTRODUCTION

Basic aspects about viral infection and structure are important to develop nanostructured materials for rapid elimination of viral particles that contaminate surfaces.

The disease COVID-19

New zoonotic respiratory viruses have emerged in humans in recent years. In 2003, in Guangdong Province, China, a highly pathogenic coronavirus caused severe acute respiratory syndrome (SARS) in more than 8,000 people in 37 different countries with 10% mortality. In 2012, a severe respiratory infection, the Middle East respiratory syndrome (MERS) (Ellis 2009, Chan et al. 2015) affected individuals in the Arabian Peninsula. In this case, a higher percentage of mortality (~ 40%), was observed that resulted from the virus capacity to promote extrapulmonary diseases and the release of viral progeny from apical and basolateral respiratory cell surfaces (Warnes et al. 2015). In late November 2019, cases of novel pneumonia (COVID-19) in Wuhan, Hubei province, China, (Andersen et al. 2020, Jiang et al. 2020) were reported, and the disease spread rapidly throughout the world and attained the status of the pandemic as declared by the World Health Organization (WHO) at 11 March 2020. There is no evidence that SARS-CoV-2 results from a genetic manipulation in the laboratory of

a pre-existent virus and there are two possible origins for the virus i) natural selection of a mutant in the animal host before transmission to a human and ii) natural selection in a human host previously infected by a zoonotic transfer (Andersen et al. 2020). SARS-CoV-2 exhibits some differences in comparison with MERS-CoV and SARS-CoV, which also cause severe diseases in humans. The receptor-binding domain (RBD) in the spike protein of SARS-CoV-2 has higher affinity with the human cell receptor (ACE2) (Wan et al. 2020) and the spike protein has a polybasic cleavage site (RRAR) at the junction of S1 and S2, which allows the effective cleavage by furin determining increasing infectivity. Accordingly, patients with COVID-19 have a higher level of inflammatory cytokines that correlates with the severity of the disease (Andersen et al. 2020).

Viral structures and infection mechanisms

Virus particles can be non-enveloped ("naked") or enveloped, the first consisting basically of the genetic material inside a protein coat named capsid, while the second have the capsid containing the viral genome, enclosed by an envelope composed by lipid bilayer associated with glycoproteins (Figure 1). Figure 1 shows

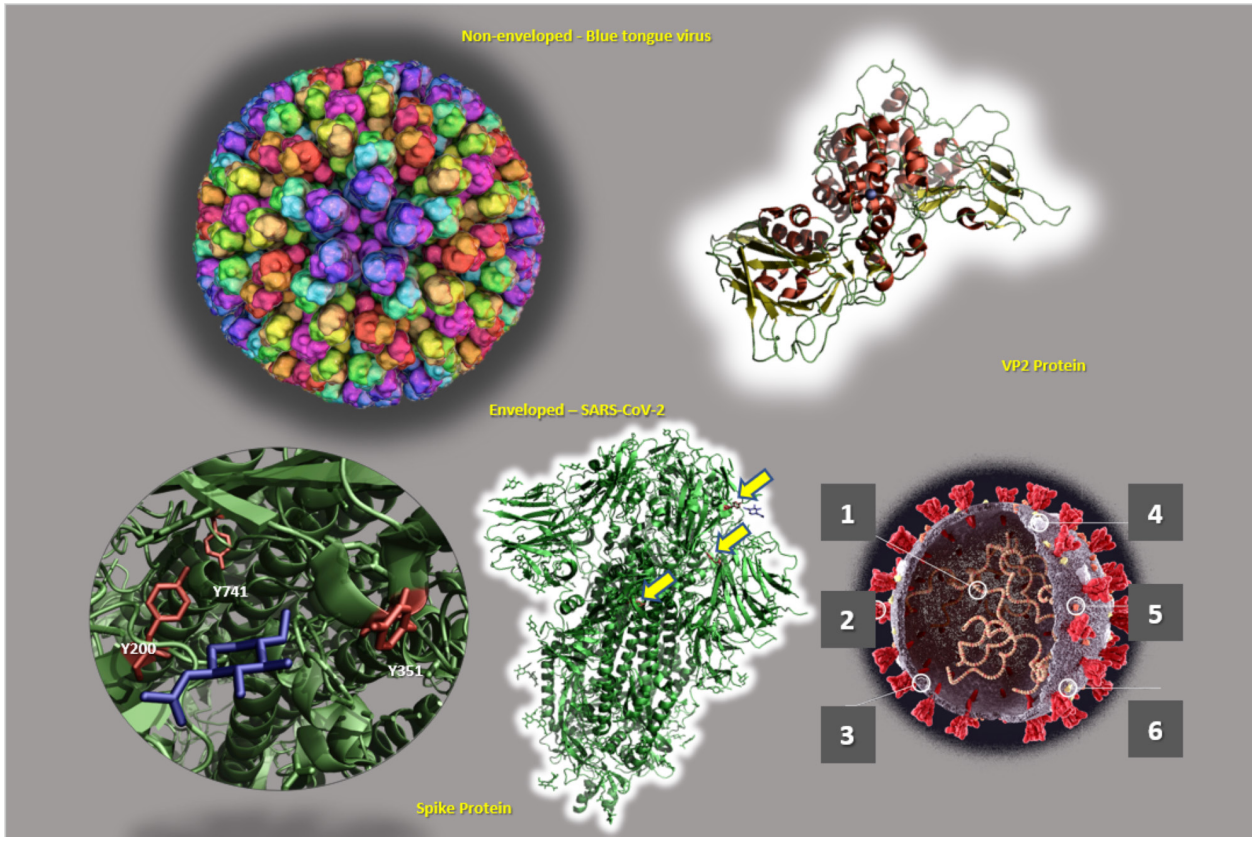

Figure 1. Viral structures represented by two virus types. In the top left it is shown an example of a non-enveloped virus, the Blue Tongue Virus (BTV), sided by the structure of one of its capsid proteins, the VP2. On the bottom right it is shown the open structure of SARS-CoV-2, an enveloped virus. The components of the SARS-CoV-2 represented in the cartoon are: 1- Nucleocapsid proteins (N) and RNA, 2- Spike protein (S), 3- Envelop lipid bilayer, 4- Hematoaglutinin (He), 5- Membrane protein (M), and 6- Envelop Protein (E). The SARS-CoV-2 representation is sided (at center) by the Spike protein (S) structure with a of a top view zoom (left) showing Y351, Y200 and Y741 in red and *N*-acetylglucosamine 1321 in violet. The yellow arrows show the position of Y351, Y200 and Y741 in the complete S protein structure.

the structure of Blue Tongue Virus (BTV) as an example of non-enveloped virus.

The infection by non-enveloped and enveloped viruses involves the following steps, the viral entry, disassembly, viral protein synthesis, production of viral genomes, assembly of viral components, and viral egress. Viral entry involves attachment to the cell followed by specific binding of viral proteins to the cellular receptors (Marsh & Helenius 2006, Brandenburg & Zhuang 2007). Glycans, which are abundant components at cell surfaces, play an important role in facilitating virus ingress in cells (Koehler et al. 2020). The binding of viral particles to receptors can trigger signalling cascades leading to endocytosis or to changes in viral structure that culminate in viral genome release into the cell. Figure 2a shows the principal strategies for viral entry in cells. One mechanism of virus entry involves the canonical endocytosis mediated by clathrin (1), or the non-canonical caveolae-mediated endocytosis that activates tyrosine kinase cascade resulting in the traffic of virus-loaded caveosome towards the endoplasmic reticulum (ER) through microtubules (2). Viruses can also enter into cells by clathrin- and caveolin-independent mechanisms (3) or direct fusion with the plasma membrane (4). The different viral strategies to enter into the cells result in similar post-endocytic trafficking mechanisms that involve the formation of dynamic and static populations of early endosomes, according to the rapid or slow maturation process (Luxton et al. 2006, Brandenburg & Zhuang 2007). The experimental strategy of single-virus tracking contributed to the mechanism of enveloped virus entry. The virus can be transported by motor proteins, dynein, and kinesin, using direct binding to these proteins or inside a motor-bound vesicle. Dynein transport cargos towards the minus extremity of microtubules, whereas kinesin is a plus end-directed motor protein (5) and (6), respectively. The transport of viral capsids to the nuclear pore (7) to deliver viral genome to the nucleus can occur by kinesin from the microtubule-organizing center (MTOC) (Brandenburg & Zhuang 2007, Zaichick et al. 2013). The completion of viral infection requires the assembly of viral components and the release of viral progeny. Figure 2b shows the mechanisms of viral particle egress from an infected cell that involves the encapsulation of viral genome in capsids to be transported by motor proteins along the microtubules (**1**) (Rietdorf et al. 2001, Brandenburg & Zhuang 2007). The viral membrane proteins expressed in host cells are transported along microtubules from the endoplasmic reticulum membrane to the Golgi apparatus (**2**). The viral capsids can bud into an envelope (**3**) or be encapsulated into multivesicular bodies (**4**). The motor protein kinesin is used to the transport of viruses- or subviral particles-loaded vesicles to the plasma membrane (**5**). Exocytosis (**6**) or budding at the plasma membrane (**7**) are the mechanisms used for the virus to exit the cells. Direct budding from the plasma membrane and signalling-mediated exocytosis are the more common pathways used to deliver the progeny of enveloped viral particles from cells. These mechanisms do not exclude the occurrence of cell lysis promoted by an enveloped virus. Lysis is the primary mechanism used by the naked virus, which can also take advantage of non-lytic mechanisms to egress from cells. Naked virus can also create new cell compartments to exit the cells by non-lytic secretory mechanisms. Non-lytic mechanisms can secrete virus- or genome-loaded vesicles, naked virus and RNA or a combination of these mechanisms (Bird & Kirkegaard 2015, Staring et al. 2018). Regarding SARS COV-2 there are pieces of evidences that SARSCoV-2 uses endocytosis or fusion at plasma for entry, depending of the cell type (Mahmoud et al. 2020). Therefore, the

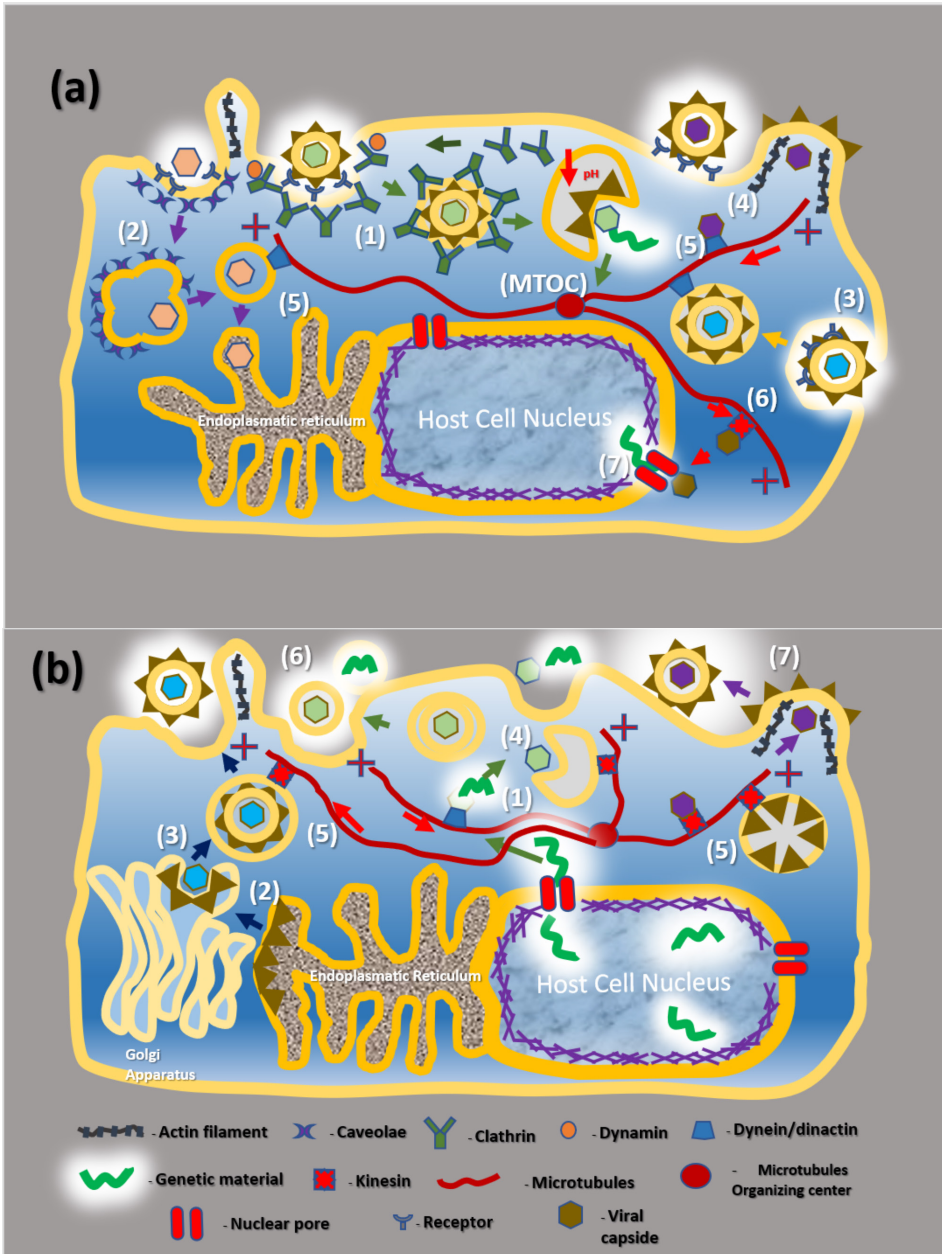

Figure 2. Mechanisms of viral entry assembly and exit from cells. a) Viral entrance and transport. Viruses bind to specific receptors on the cell surface and can use canonical and non-canonical endocytic pathways to enter into cells. The canonical endocytic pathways consist of clathrin-coated vesicles with the participation of GTPase dynamin (1); the caveolin-dependent endocytosis (2); the clathrin- and caveolin-independent endocytosis (3), and direct fusion with the cell membrane (4). Virus-loaded vesicles use motor proteins dynein or dynactin for the transport along microtubules on the road to the microtubule-organizing center (5) (MTOC). From the MTOC, capsids can be transported by kinesin towards the replication site of the nucleus (6). Some viruses release their genetic material into the cytosol, whereas others transport their genomes into the nucleus (7); b) Viral assembly and exit from cells. Viral genomes are packed in capsids for transport lengthways microtubules (1); The viral membrane proteins are synthesized in the endoplasmic reticulum are transported to Golgi apparatus and directed to the site of viral assembly (2); the viral capsids can bud into an envelope (3) or encapsulated into multivesicular bodies (4); viruses- or subviral particles-loaded vesicles, are transported by kinesin along microtubules to attain the plasma membrane (5); the vesicles can egress from the cell by exocytosis (6) or budding (7) at the plasma membrane.

endocytic mechanism of SARS-CoV-2 must be considered according to the host cell type to be studied and understanding the mechanisms of viral entry is important for the finding of effective therapeutic agents in the treatment of COVID-19 (Glebov 2020).

SURFACES AS A SOURCE OF VIRAL INFECTION

Surface contamination has been recognized as an essential contributor to the spread of diseases. Infected and symptomatic individuals promote constant recontamination of surfaces that are then touched by non-infected persons leading to a rapid dissemination of the disease (Figure 3). Similarly to the previous coronaviruses of high infectious potential, MERS-CoV and SARS-CoV, and considering the unprecedented capacity of SARS-CoV-2 spread, it is likely that prolongated virus viability on contaminated surfaces has a significant contribution in viral spread. (Warnes et al. 2015). Firquet et al. (2015) determined the viability of non-enveloped and enveloped viruses on surfaces under repetitive cycles of drying and resuspension (Firquet et al. 2015). The viruses that were used in their study were the naked minute virus of mice (MVM) and coxsackievirus B4 (CVB4) and the enveloped-viruses influenza A virus (H1N1) and herpes simplex virus type 1 (HSV-1). In the case of CVB4, the influence of the initial protein and sodium chloride concentrations was also studied. The results demonstrated that enveloped viruses were less resistant than the naked viruses. The presence of proteins increased the impact of drying, while sodium chloride had a protective effect. Recently, van Doremalen et al. (2020) compared the stability of SARS-CoV-2 with that of SARS-CoV-1 in aerosol and surfaces and showed that both have similar stability in the assayed conditions (van Doremalen et al. 2020).

The study aimed to investigate whether the differences in the epidemiologic characteristics of these viruses arise from significant differences in the resistance on surfaces and aerosols. The authors concluded that the epidemiologic differences likely result from other factors related to the capacity of infected asymptomatic individuals to spread the virus and the presence of high viral load in the upper respiratory tract

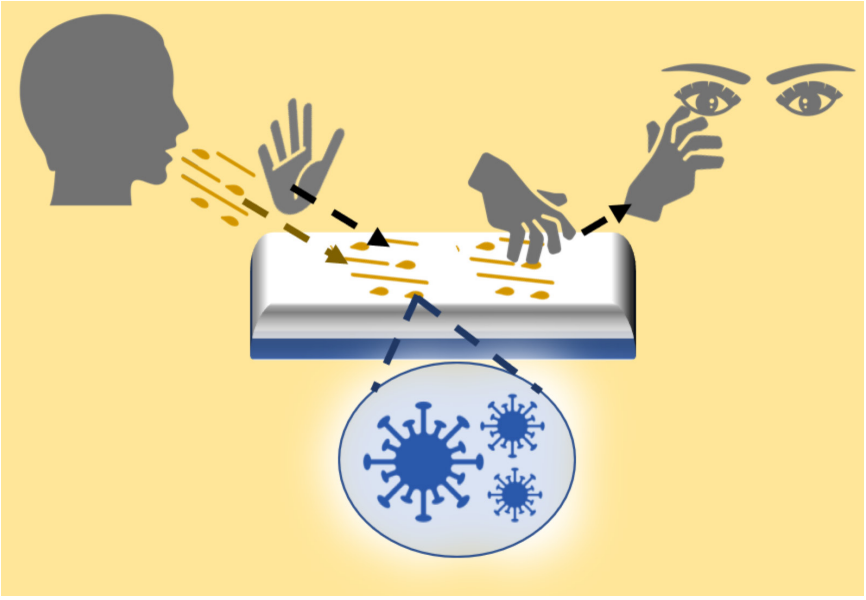

Figure 3. Mechanisms of viruses' dissemination by surface contamination. Fluid droplets containing virus from an infected and symptomatic person can be spread by a cough or sneeze and attain a surface directly or by the touch of the contaminated hand. Other non-infected persons can be contaminated by touching the contaminated surface and leading viral particles to the face.

(Bai et al. 2020, van Doremalen et al. 2020). As illustrated in Figure 2, the authors concluded that similarly to SARS-CoV, the virus SARS-CoV-2 can easily be propagated via respiratory droplets spread by cough, sneeze, speech, and aerosol of the nosocomial environment. The virus present in droplets can remain viable on surfaces up to several days leading to dissemination by touching dirty/contaminated surfaces with subsequent self-inoculation by touching eyes, nose, and mouth (Bai et al. 2020, van Doremalen et al. 2020). SARS CoV-2 has higher transmission rates compared to the other human coronavirus, such as SARS-CoV and MERS (Liu et al. 2020, Sportelli et al. 2020). The high transmission rates associated with the absence of pre-existing immunity of the population, lack of specific and efficient treatments, and vaccines make the prevention as the most effective way to combat the COVID-19 (Sportelli et al. 2020). Social confinement is efficient and mandatory to prevent rapid dissemination of SARS-CoV-2, but it is not possible for the entire population since essential services such as food, medicine, and hospital care should be available. Furthermore, at the initial period of return to work after confinement, it is imperative to have sufficient availability of efficient personal protective equipment (PPE) (Sportelli et al. 2020). Therefore, besides the search for anti-SARS-CoV-2 drugs and vaccines, another critical aspect of the combat of viral epidemics is the development of personal protective equipment such as masks and gloves with biocidal properties provided by different additives. Self-decontaminating surfaces constitute an additional strategy towards preventing transmission in a diversity of situations. The chemical and photochemical biocide activity can result from the intrinsic properties of the material or by association with organic molecules with biocide properties (Zhou et al. 2010, Hodek et al. 2016, d'Amora & Giordani 2018). A recent study performed by van Doremalen et al. (2020) investigated the capacity of SARS-CoV-2 to remain viable on different material surfaces, and the results were similar to the previous work performed with Human Coronavirus 229E (Warnes et al. 2015, van Doremalen et al. 2020). Plastic and stainless steel are materials that preserve the virus viability for longer times, whereas copper surface was most favourable for virus inactivation. The virucidal property of copper is assigned to the production of reactive oxygen species. The virucidal activity of the oxygen reactive species led to an increased interest in the use of nanostructures to produce materials for disinfection purposes. The nanostructured materials can provide biocide action through chemical and photochemical activity.

VIRUCIDAL NANOSTRUCTURED MATERIALS

Literature data have reported that different nanostructured materials exhibit virucidal activity provided by the intrinsic properties of the materials such as the production of reactive oxygen species, by the capacity to act as drug delivery or to potentialize the action of some pharmaceuticals. Typical materials that can contribute to virus destruction are silver nanoparticles (AgNPs) (Lara et al. 2010, 2011), metal oxides mainly, copper and iron oxide (Borkow et al. 2010, Kumar Mishra et al. 2013, Kumar et al. 2019), hybrid materials (Hodek et al. 2016), organic polymeric nano/microstructures, (Ciejka et al. 2017) and nanostructured carbon materials (d'Amora & Giordani 2018, Pedrosa et al. 2019). Many studies involving gold and silver nanoparticles have focused on the use as carriers of drugs, potentiating the medication. However, the purpose of this review is to discuss the use of nanostructures to prevent viruses,

especially by developing self-disinfecting materials. Another aspect of prevention that can count on the help of nanostructured materials is the development of faster and more efficient diagnostic platforms, that requires approaching in a specific review.

Gold and silver nanoparticles

The materials acquire specific properties at the nanoscale, as depicted in Figure 4. The decrease in the size of a bulk metallic material to the nanoscale changes the electronic structure of the conduction band, replacing the continuum density of states by a set of discrete energy levels and opening a bandgap.

There is an increase of bandgap energy accompanying the size decrease of a material to the nanoscale, and the nanostructured metals can behave as a semiconductor (Gleiter 2000, Steinhart 2004, Roduner 2006, Aneesh et al. 2014, Charra et al. 2018, Brito et al. 2019) (Figure 4). The effect of resonance resulting from the interaction of conduction electrons of metal nanoparticles with incident photons is the surface plasmon resonance (SPR) (Jana et al. 2016). The interaction is dependent on the size and shape of the metallic nanoparticles as well as on the composition and nature of the medium used for dispersion (El-Sayed et al. 2006, Austin et al. 2014, Kabb et al. 2015, Jana et al. 2016). Figure 4 shows, on the right side, the events associated with direct excitation of metallic nanoparticles that can be used for virus inactivation (González-Béjar et al. 2013, Jana et al. 2016). The plasmon relaxation of metallic nanoparticles produces very high temperatures (González-Béjar et al. 2013, Riedinger et al. 2013) that can inactivate the virus by inducing chemical and supramolecular changes. The plasmon excited particle can donate holes or electrons directly to virus biomolecule or water and molecular oxygen leading to the production of reactive species for the pathogen inactivation. The antenna effect can, for instance, raise the excitation rates of a quantum dot (QD) leading to higher yield of fluorescence and reactive species (Holzinger et al. 2014). Thus, AgNPs and AuNPs, when associated with different

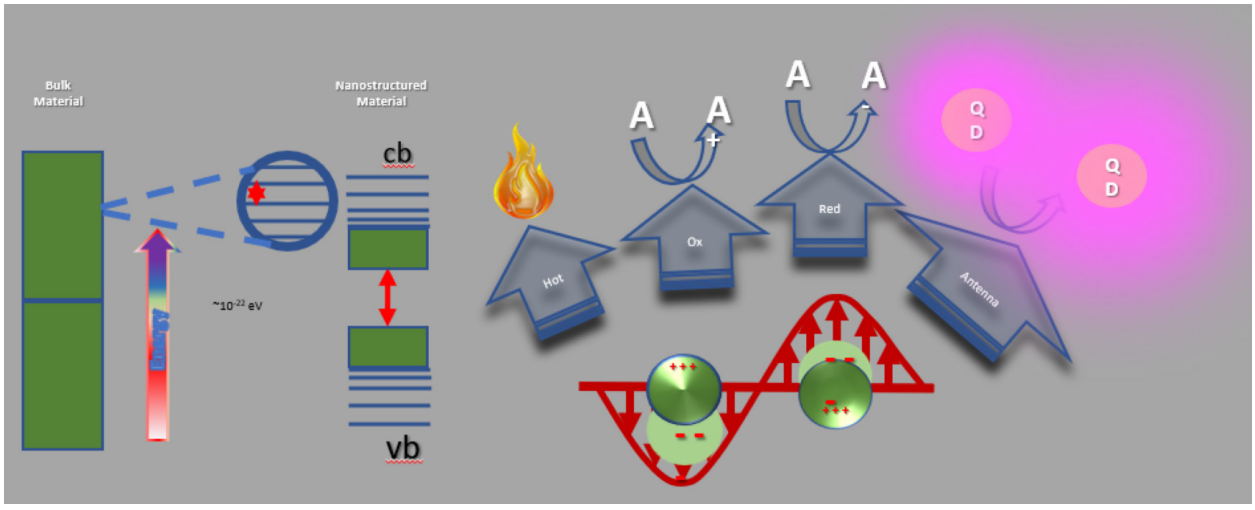

Figure 4. Specific optoelectronic properties and applications of metallic nanoparticles. On the left side, is shown the increase of the bandgap energy and the density of states associated with the diminution of the number of atoms constituting a particle with the representation of material valence and conduction bands (*vb* and *cb*). On the right side, possible events after plasmon excitation of metallic nanoparticles: thermal, redox reactions, and antenna. The figure is inspired by the references (González-Béjar et al. 2013, Brito et al. 2019).

matrices such as polymers and textiles, can give virucidal properties for these materials (Simoncic & Tomsic 2010, Gadkari et al. 2020). Films of poly (3-hydroxybutyrate-co-3-hydroxy valerate) (PHBV) associated with AgNPs revealed an efficient virucidal activity. The material inactivated feline calicivirus (FCV) and 86% of murine norovirus (MNV) within 24 h exposure at 37° C (Castro-Mayorga et al. 2017). In textiles, AgNPs are used mainly against bacteria, and nowadays, these nanoparticles have also been recognized as virucides. Regarding the production of silver nanoparticles, they can be produced *in situ* by a photochemical method and remain decorating the surface of polymers as the example that is shown in Figure 5. The events of hyperthermia and the production of reactive oxygen species metallic nanoparticles have been extensively used for anti-tumor therapies. In this regard, the absorption of red light is desirable because the deep penetration in tissues. Many green, rapid, and one-pot methods are currently available for Au and Ag NPs synthesis, such as those that have been developed by our research group (Miranda et al. 2016, Tofanello et al. 2016, Cruz et al. 2018, Santos et al. 2020). The spectral range of light absorption can be modulated by the size, shape, and aggregation state of the nanoparticles. To achieve virus inactivation, it is crucial to have the production of reactive species by absorption of UV and visible light from sun and artificial light sources. Therefore, the combination of different nanoparticles regarding their size, shape and composition is an interesting strategy for best use of UV and visible spectra to produce reactive species against virus.

Figure 6 shows the snapshot and the corresponding spectra of the colloidal dispersion of nanorods (NRs) with increasing aspect ratio. At left, the flask with the brownish solution is the seed suspension used for preparing the NRs. Other promising metallic nanostructures for the fabrication of materials with virucidal properties are the Ag/Halogens-NPs (Araújo et al. 2017, 2018, Cruz et al. 2018) that exhibited efficient photocatalytic activity on the removal of dyes. Considering that the bleaching of dyes is associated with the production of reactive oxygen species, these nanoparticles are promising for virus inactivation.

Carbon nanostructured materials

The electronic, mechanical, and magnetic properties of carbon nanostructures (CNSs) have been extensively studied (Chand 2000, Zhu & Xu 2010, Kukovecz et al. 2013, Ahn & Hong 2014, Lim et al. 2015, Champi et al. 2016, Karousis et al. 2016, Acatay 2017, Liu et al. 2018, Ferreira et al. 2018, Pochkaeva et al. 2020).

The CNSs have a diversity of applications including to act as powerful microbicide agents. Complex mechanisms respond for the capacity of CNSs to inactive virus, fungi and bacteria that is dependent of type of microorganism, the intrinsic material properties and environmental conditions.(Al-Jumaili et al. 2017). The physical interaction of CNSs is able to promote structural changes in the microorganisms biomolecules causing damages in bacteria membranes, virus capsid and envelope.(Kholmanov et al. 2012, Dizaj et al. 2015, Al-Jumaili et al. 2017). As an example, graphene oxide conjugated with a nonionic polymer, polyvinylpyrrolidone (PVP) showed potent anti-viral activity which did not occur when combined with a cationic polymer, polydiallyldimethylammonium (PDDA). Also, GO promoted structural destruction of the virus before cell entry supporting GO as a novel promising anti-viral agent. (Ye et al. 2015). Table I summarizes structural features and general and microbicide properties of CNSs and Figure 7 illustrates virus inactivation by GO.

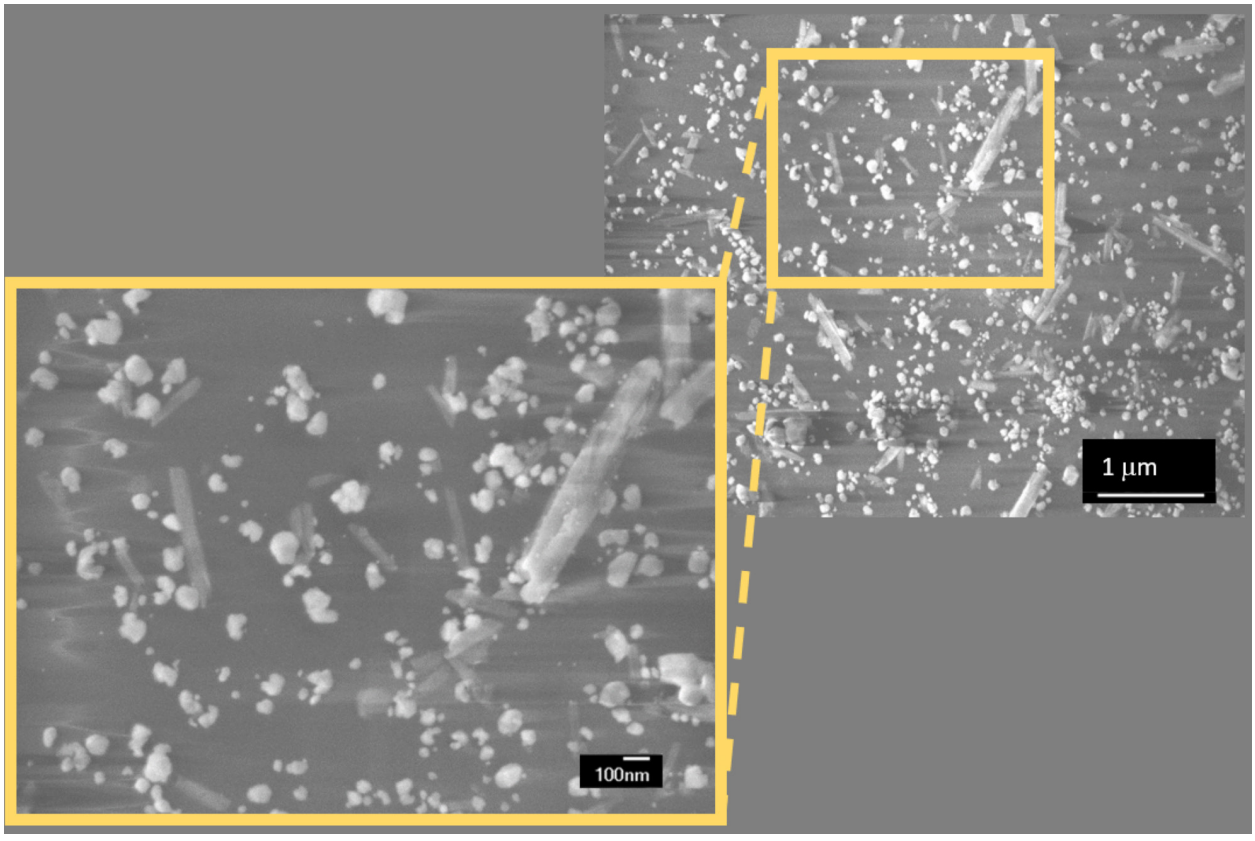

Figure 5. Field Emission Scanning Electron Microscopy (FESEM) of organic polymer decorated with AgNPs produced photochemically by using the reducing power of a thiazinic dye irradiated with visible light according to an adaptation of the method described in the literature (Santos et al. 2020).

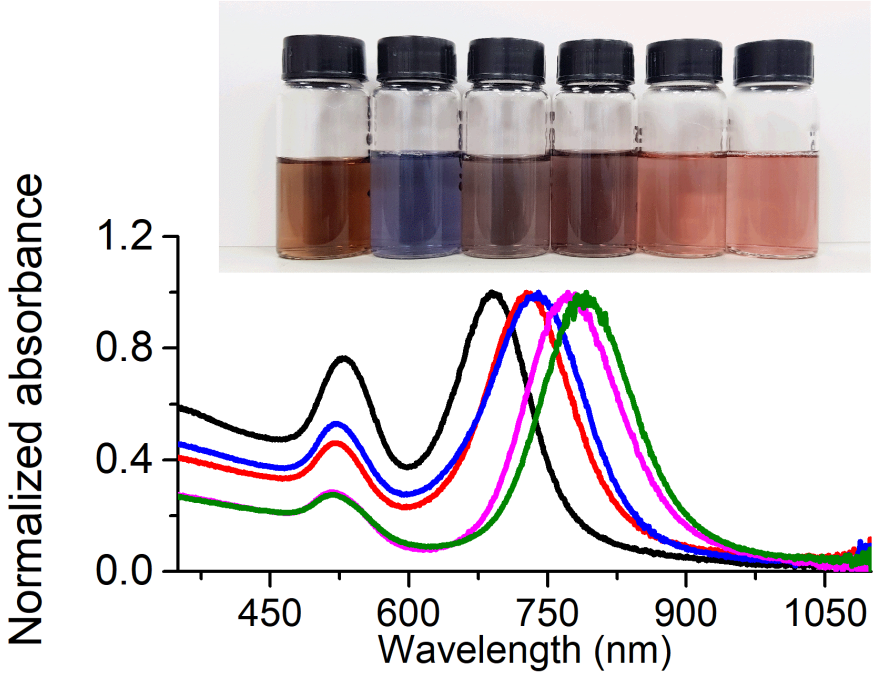

Figure 6. Spectra and colloidal suspension of gold nanorods (NRs). In the snapshot, the NR aspect ratio increases from left to right. The peaks of the lower energy band are redshifted with the increase of the NR aspect ratio.

Table I. Structure and Applications of CNSs.

CNS	Structure	Usual Potential Applications	Microbicide capacity
Carbon black	Spherical particles of carbon aggregated and fused together. Carboxylic groups can be present (Tofighy & Mohammadi 2019).	Rubber or polymer fortification, catalysis, pigments and electrodes (Ali et al. 2017, Tofighy & Mohammadi 2019).	Against bacteria. Composite with chitosan and metallic nanoparticles Carbon black (Ali et al. 2017)
Carbon fiber	Graphene sheets twisted, folded and shattered upon each other (Acatay 2017).	Aerospace and nuclear engineering for devices submitted high damping, extreme temperatures and corrosive environments. Template for nanostructure growing.(Chand 2000, Acatay 2017, Liu et al. 2018)	Against bacteria. Fibers impregnated with silver (Le Pape et al. 2002)
Fullerene	Closed cage Structure with icosahedral symmetry formed by 20 hexagonal and 12 pentagonal rings. (Pochkaeva et al. 2020).	Electrocatalysis in fuel cells, diversity of biomedical applications (Pochkaeva et al. 2020)	Against HIV Water-soluble fullerene derivatives with carboxy, hydroxy groups, derivatives with amino acids, peptides and proteins. (Arts & Hazuda 2012, Strom et al. 2015, d'Amora & Giordani 2018, Pochkaeva et al. 2020)
Graphene	Crystalline allotrope in the form of a 2D, atomic-scale, structured as a hexagonal lattice with carbon atoms with sp2 hybridization.(Novoselov 2004)	Graphene has potential to be applied from flexible electronics to DNA sequencing. Few graphene-based products have reached the market that requires large-scale production. (Torrisi & Coleman 2014, Ahn & Hong 2014, Böhm 2014, Drndić 2014, Kostarelos & Novoselov 2014, Siochi 2014).	Against bacteria and virus Microbicide activity is associated to physical contact and oxidative stress. (Ye et al. 2015, Perreault et al. 2015)
Carbon nanotubes	Carbon nanotube (CNT) is formed by graphene wrapped in the shape of a cylinder and bonded together to form a carbon nanotube. This material exists as single- and multiwalled forms.(Nanot et al. 2013, Kukovecz et al. 2013)	The applications are reported for energy conversion and storage, electronics, semiconductor devices, capacitors, hydrogen storage, catalysis, composite materials of owned of high-strength and conductive properties, batteries, several sensors; field emission displays, interconnects and others. There are some products using carbon nanotubes such as bicycle frame, antifouling CNT paints, printed electronics, electrostatic discharge shielding reported for Juno spacecraft uses, CNT ESD shield. (Baughman et al. 2002, Sun et al. 2002, Schnorr & Swager 2011, Zhi et al. 2013, De Volder et al. 2013)	Against bacteria and HIV, more common use in filters against virus and bacteria (Cheng et al. 2010, Vecitis et al. 2011, Rahaman et al. 2012, Banerjee et al. 2012, Al-Jumaili et al. 2017)

Carbon nanohorns	Carbon nanohorns are similar to carbon nanotube but it is shaped as a conical single-walled tip. Carbon nanohorns are constructed from an sp^2 carbon sheet (Zhu & Xu 2010, Karousis et al. 2016)	Carbon nanohorns have potential applications in capacitors, gas adsorption, catalysis, sensing, and drug delivery. One of the most auspicious applications is in the biological area.(Zhu & Xu 2010, Zhang et al. 2015, Karousis et al. 2016)	Carbon nanohorns produces reactive oxygen species and can eliminate microorganisms. It is described photo-induced inactivation of virus by carbon nanohorns.(Miyako et al. 2008)
Carbon quantum dots	Carbon quantum dots are described as quasi-spherical nanostructures including amorphous to nanocrystalline centers. The cores have predominance of sp^2 carbon or sheets of graphene and graphene oxide bonded by diamond-like sp^3 hybridised carbon insertions.(Lim et al. 2015)	Carbon quantum dots are materials with tunable fluorescence and have potential application in chemical sensing, biosensing, bioimaging, nanomedicine, photo and electrocatalysis (Wang & Hu 2014, Lim et al. 2015, Fernando et al. 2015)	Against microorganisms including vrus JEK, ZIKV, DENV, PPV, AAV, PK-15, MARK-45 and others. (Huang et al. 2019, Dong et al. 2020)

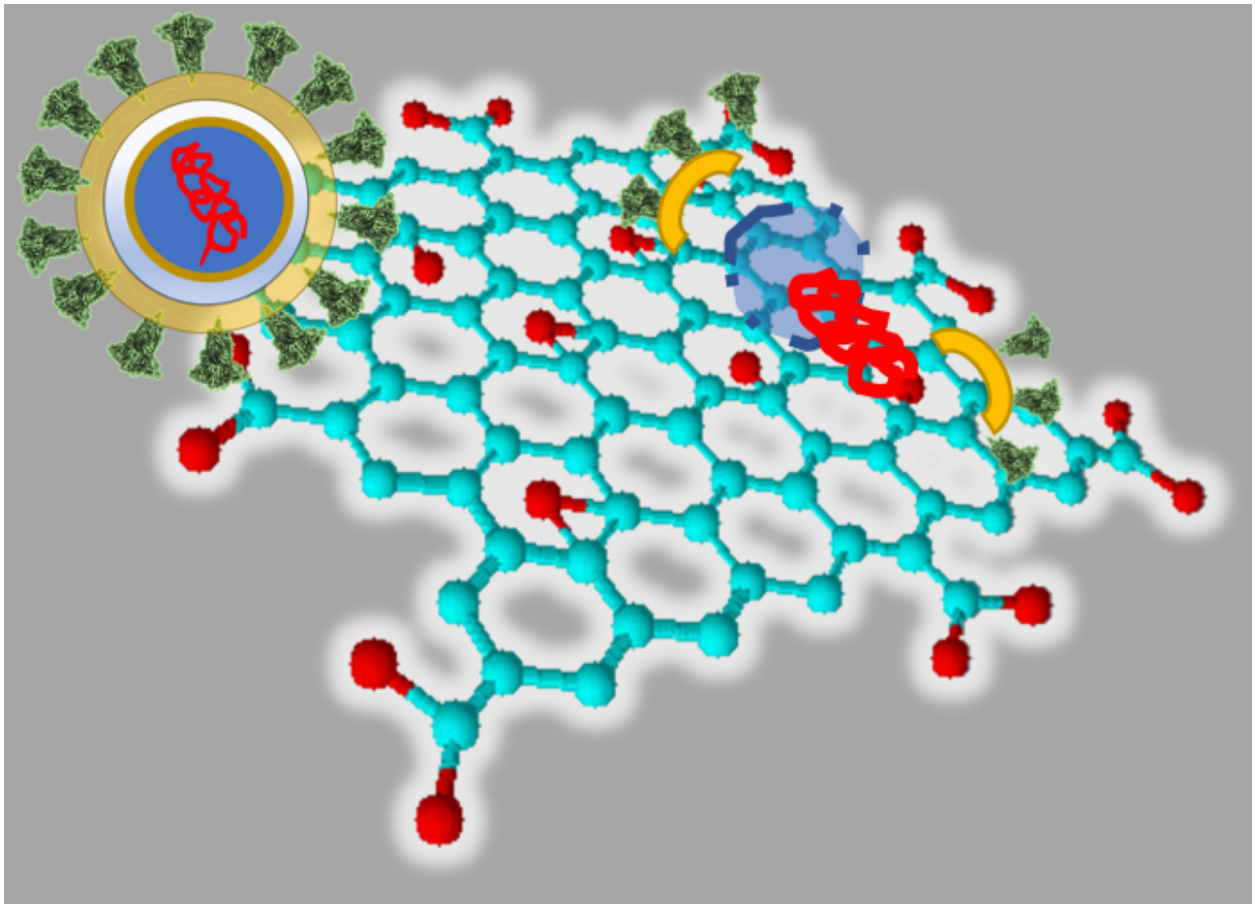

Figure 7. Representation of a GO layer with a virus before and after inactivation with RNA liberation. RNA is represented as a red curled line, virus envelope in yellow, oxygen in red, and carbon in blue.

Nanostructured metal oxides

Nanostructured metal oxides hematite (α-Fe_2O_3), goethite (α-FeOOH), magnetite (Fe_3O_4), amorphous iron(III) hydroxide ($Fe(OH)_3$), titania nanostructures (anatase nanoparticles and titanate nanotubes) and zinc oxide (ZnO), are also efficient for the fabrication of textiles with virucidal properties (Sang et al. 2007, Dias et al. 2012, Nakano et al. 2012, Nieto-Juarez & Kohn 2013, Ruales-Lonfat et al. 2015, Zeedan et al. 2020, Menezes et al. 2020). The well-known production of reactive oxygen species by these materials under illumination is promising for a large scale use in the fabrication of self-disinfecting materials (Yan et al. 2009, Menezes et al. 2019, 2020).

Semiconductors such as iron oxides, ZnO and TiO_2 are well known for the capacity to produce, under irradiation, and even in the dark, oxidative species such as hydroxyl radical ($OH^{\cdot}$), superoxide ion, hydrogen peroxide (H_2O_2), and singlet oxygen ($^1\Delta_g O_2$) (Rao et al. 1980, Macyk et al. 2006, He et al. 2014) that can promote oxidative damages in biomolecules like proteins (Estevam et al. 2004, Rodrigues et al. 2007). The irradiation of the semiconductor generates the superoxide ion ($O_2^{\cdot-}$) by electron transfer from *cb* to molecular oxygen. Singlet oxygen can also be produced by energy transfer to molecular oxygen that occurs associated with the h^+/e^- recombination (Macyk et al. 2006). Therefore, semiconductors are materials with high potential for virus inactivation. Importantly, our research group has developed green methods for the production of nanoparticles of metal oxides, including magnetite nanoparticulated (Nantes-Cardoso & Tofanello de Souza 2019) and Co_3O_4 (unpublished results). The association with metallic nanoparticles can also improve the property of self-disinfection. In the case of hematite (α-Fe_2O_3), it is possible to produce hierarchically layered Fe_3O_4/Fe_2O_3 microtubes and foils with the respective Fe_2O_3 nanowires (Fe_2O_3NWs) and Fe_2O_3 nanoflakes (Fe_2O_3NFs) vertically protruding at the surface as shown in Figure 8 (Pomar et al. 2018). These materials were used for their self-decoration with gold nanoparticles produced *in situ* from $AuHCl_4$ solutions by using the photochemical properties of Fe_2O_3 (Menezes et al. 2020). Figure 8 shows the FESEM images of Fe_2O_3NWs(NFs) with the surface extensively decorated by gold nanoparticles. A diversity of nanostructured oxides (Figure 9) can be produced using two principal methodologies: (a) electrospinning and (b) hydrothermal synthesis. Oxides such as the electronically related system $RNiO_3$ (R = La, Nd), TiO_2, and the superconductor YBa_2 $(Cu1\text{-}_xNi_x)_3O_4$ can also be prepared by this electrospinning. (Chiquito et al. 2007, Giraldi et al. 2007, Barbeta et al. 2011, Zenatti et al. 2013, Jardim et al. 2015, Medina et al. 2020a). Hydrothermal synthesis has been used for the synthesis of more complex oxides such as the multiferroic $BiFeO_3$, the thermoelectric oxide $Ca_3Co_4O_9$, $LaNiO_3$, and simple oxides such as TiO_2, SnO_2, and Co_3O_4 (Medina et al. 2020b).

Therefore, a diversity of nanostructured materials can be incorporated in different matrices to produce textiles and objects with self-disinfecting properties provided by the production of reactive oxygen species when the materials are exposed to illumination. Figure 10 illustrates the proposal of a mask fabricated with a textile impregnated with a nanostructured semiconductor.

NANOSTRUCTURED MATERIALS FOR BIOSENSOR FABRICATION

Besides the application in self-disinfecting devices, the studies on the interaction of the enveloped viruses with nanostructured

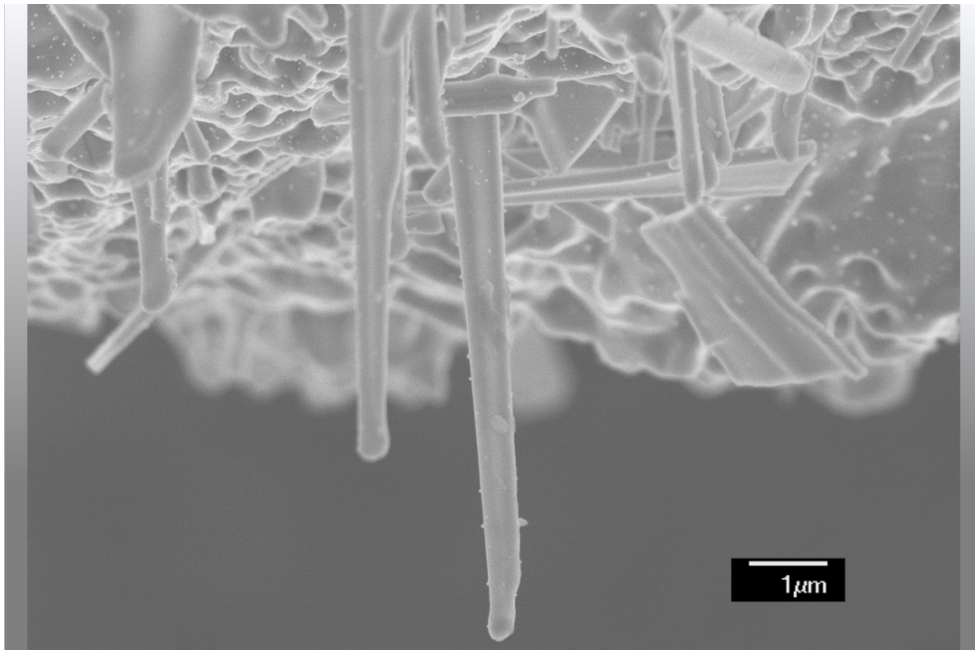

Figure 8. FESEM images of microtube and foil with hematite surface. The 10,000 x magnification image of the hematite surface with nanowires protruding from the surface shows gold nanoparticles decorating the material surface.

materials can also address another critical issue that is the detection of the virus for diagnosis, preferentially at the initial stages of the disease.

Diagnosis is the primary strategy for the control of the viral dissemination and to treat viral infection. Several new approaches based on nanostructured materials have recently been established. Studies have reported the use of gold and silver nanoparticles, magnetic nanoparticles, carbon and polymeric nanostructured materials (Cao et al. 2002, Yang et al. 2010, Theek et al. 2014, Ye et al. 2015, de Souza et al. 2016, Ciejka et al. 2017). Gold nanoparticles are particularly exciting and commonly described to be appropriated for many applications. The photonic, electric, and catalytic properties of gold nanoparticles and particularly the specificity for functional groups present in biomolecule structures, allow designing a wide range of virus detection systems (Rashid & Yusof 2017). Graphene oxide, their derivatives, and in association with metallic nanoparticles have also been applied in electrochemical biosensors for virus detection (Peña-Bahamonde et al. 2018. ig. 102018, Singh et al. 2019).

HAZARDS FOR THE USE OF NANOSTRUCTURED MATERIALS FOR THE SELF-DISINFECTION OF SURFACES

The growing application of nanotechnology has brought benefits, but also risks to human health and the environment (Joshi & Bhattacharyya 2011, Ferdous & Nemmar 2020, Tortella et al. 2020, Hadrup et al. 2020). The toxicological and environmental risks arising from the application of nanotechnology are present in the stages of manufacture, handling, use and disposal of materials. For the human health, the inhalation is an important via of adverse effects of nanostructured materials. The contamination during fabrication and by unappropriated discard are the principal risks of ecotoxicity. The toxicity of nanomaterials depends on a variety of factors such as composition, shape, size,

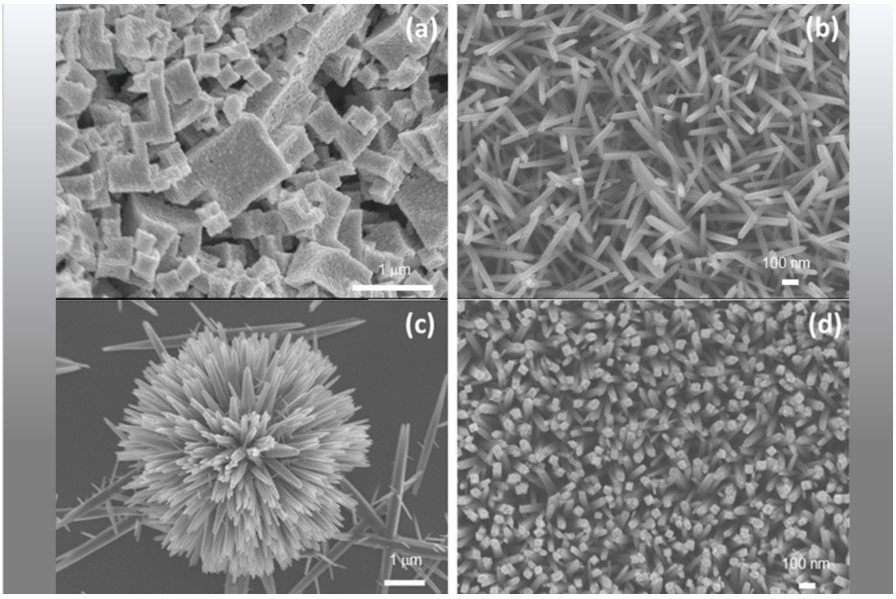

Figure 9. SEM images obtained for samples synthesized by the hydrothermal method: (a) $LaNiO_3$ nanocubes; (b) rutile nanoneedles grown on FTO/Si (100) (c) rutile nanoneedles grown on Si (100) and (d) rutile nanoneedles.

aggregation, stability, among others. The effects are also varied depending on the species, the degree of development and the tissue affected (Walters et al. 2016, Duhan et al. 2017, Gonzalez & Johnston 2018). In this sense, it is difficult to establish a comprehensive toxicity ranking for all types of nanostructures. Regarding the application of nanotechnology for microbicidal purposes, silver nanoparticles have been the most commonly used. For this reason, a large number of researches have been concerned with determining the toxic effects of silver nanoparticles. (Joshi & Bhattacharyya 2011, Ferdous & Nemmar 2020, Tortella et al. 2020, Hadrup et al. 2020) The available studies about silver nanoparticles toxicity make evident that these nanomaterials are not unharmful and careful is necessary for manipulation and discard of products containing silver nanoparticles. It is important to address carefully the use of silver nanoparticles particularly in textiles that demands frequent wash and discardable materials. The unique properties of CNSs allow the applications of these engineered nanomaterials in the computer, smart textiles, electronic devices, medicine, aerospace, and others. Therefore, the well-known cytotoxicity of CNSs must be considered for the production of self-disinfecting materials. The CNSs are an optimum example of materials that are inert in the bulk and harmful in the nanostructured form. (Lam et al. 2006). Regarding the use of metal oxide nanoparticles, some studies show a ranking of toxicity that varies according to the parameter that is evaluated (Liu et al. 2015, Ha et al. 2018). Pusyn et al and Mu et al used the quantitative structure–activity relationship (QSAR) method to predict the toxicity of various metal oxides. The authors based on experimental testing obtained for nanotoxicity to bacteria and obtained a good agreement of the theoretical with the experimental data (Table II) (Puzyn et al. 2011, Mu et al. 2016).

Thus, it is very important to give priority to green and sustainable methods of nanoparticle synthesis, to use PPE when handling them, to prefer materials that produce reactive oxygen species rather than those that produce ions to destroy the virus, to choose methods of incorporating nanostructures in fabrics that

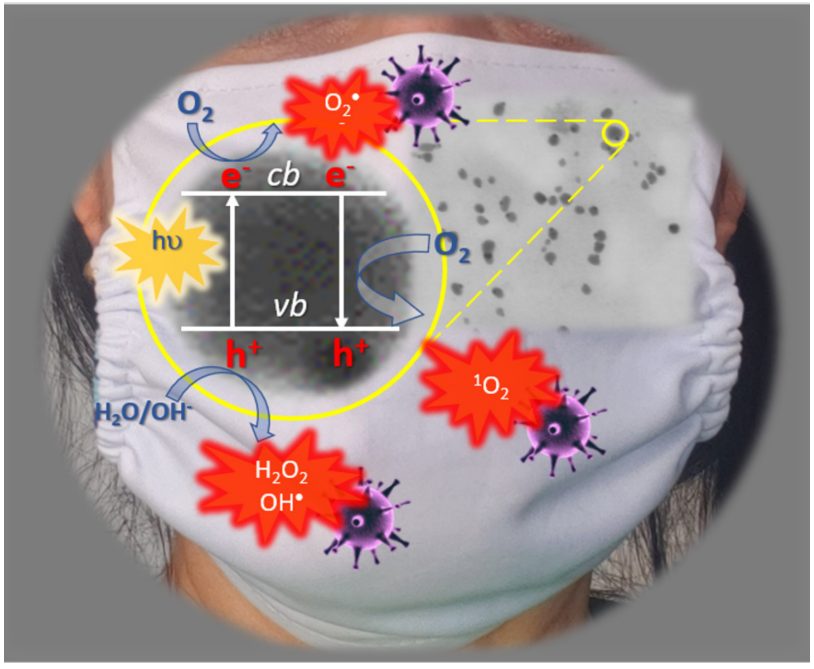

Figure 10. A proposed self-disinfecting mask that is taking advantage of the reactive oxygen species produced by metal oxide nanoparticles that were impregnated in the textile.

Table II. Observed and Predicted Toxicity of Metal Oxides.

Metal Oxide	Observed Log $1/IC_{50}$ ($mol.l^{-1}$)	Predicted Log $1/IC_{50}$ ($mol.l^{-1}$)
ZnO	3.45	3.30/3.39*
CuO	3.2	3.24/3.35*
V_2O_3	3.14	2.74
Y_2O_3	2.87	3.08
Bi_2O_3	2.82	2.69
In_2O_3	2.81	2.52
Sb_2O_3	2.64	2.57
Al_2O_3	2.49	2.63
Fe_2O_3	2.29	2.35
SiO_2	2.20	1.99
ZrO_2	2.15	2.41
SnO_2	2.01	1.95
TiO_2	1.74	2.13/1.95*
CoO	3.51	3.38/3.39*
Co_3O_4	-	2.94
NiO	3.45	3.38/3.42*
CrO_3	2.51	2.52
La_2O_3	2.87	2.85

*According to Mu et al. 2016.

provide strong adhesion of these materials and properly dispose of waste containing nanostructures.

CONCLUSIONS

In addition to the development of anti-viral medicines and vaccines, the combat of viral infections should include the production of self-disinfecting materials. This preventive strategy has the advantage that can be of applied to a diversity of viruses and other pathogenic microorganisms. Nowadays, a diversity of nanostructured materials can be produced, and most of them by green, facile, one-pot methods. The intrinsic capacity of these materials to produce reactive oxygen species under illumination with visible light makes them promissing for the development of a lot of objects and textiles that are able of virus inactivation. However, it is necessary to pay attention to the fabrication, manipulation, and discard of products containing nanostructured materials to avoid hazardous effects to human health and environment.

Acknowledgments

The authors thank FAPESP 2015/017688-0, 2017/02317-2, SisNano (402289/2013-7), NBB/UFABC, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES grant 001), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (309247/2017-9), for the financial support, CEM/UFABC for the access to facilities, David da Mata Lopes for the technical assistance. V.H.T is a fellow of Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) (2019/26919-7). Professor Ana Champi thanks 2MI and VRS Eireli Research & Development for the financial support.

REFERENCES

ACATAY K. 2017. Carbon fibers. p. 123-151 Fiber Technology for Fiber-Reinforced Composites. Elsevier.

AHN J-H & HONG BH. 2014. Graphene for displays that bend. Nat Nanotechnol 9: 737-738.

AL-JUMAILI A, ALANCHERRY S, BAZAKA K & JACOB M. 2017. Review on the Antimicrobial Properties of Carbon Nanostructures. Materials (Basel) 10: 1066.

ALI F, KHAN SB, KAMAL T, ANWAR Y, ALAMRY KA & ASIRI AM. 2017. Bactericidal and catalytic performance of green nanocomposite based-on chitosan/carbon black fiber supported monometallic and bimetallic nanoparticles. Chemosphere 188: 588-598.

ANDERSEN KG, RAMBAUT A, LIPKIN WI, HOLMES EC & GARRY RF. 2020. The proximal origin of SARS-CoV-2. Nat Med 89: 44-48.

ANEESH PK, NAMBIAR SR, RAO TP & AJAYAGHOSH A. 2014. Electrochemical synthesis of a gold atomic cluster-chitosan nanocomposite film modified gold electrode for ultra-trace determination of mercury. Phys Chem Chem Phys 16: 8529-8535.

ARAÚJO JN, TOFANELLO A, DA SILVA VM, SATO JAP, SQUINA FM, NANTES IL & GARCIA W. 2017. Photobiosynthesis of stable and functional silver/silver chloride nanoparticles with hydrolytic activity using hyperthermophilic β-glucosidases with industrial potential. Int J Biol Macromol 102: 84-91.

ARAÚJO JN, TOFANELLO A, SATO JAP, CRUZ LS, NANTES-CARDOSO IL, FERREIRA FF, BATISTA BL & GARCIA W. 2018. Rapid Synthesis via Green Route of Plasmonic Protein-Coated Silver/Silver Chloride Nanoparticles with Controlled Contents of Metallic Silver and Application for Dye Remediation. J Inorg Organomet Polym Mater 28: 2812-2818.

ARTS EJ & HAZUDA DJ. 2012. HIV-1 Antiretroviral Drug Therapy. Cold Spring Harb Perspect Med 2: a007161-a007161.

AUSTIN LA, MACKEY MA, DREADEN EC & EL-SAYED MA. 2014. The optical, photothermal, and facile surface chemical properties of gold and silver nanoparticles in biodiagnostics, therapy, and drug delivery. Arch Toxicol 88: 1391-1417.

BAI Y, YAO L, WEI T, TIAN F, JIN D-Y, CHEN L & WANG M. 2020. Presumed Asymptomatic Carrier Transmission of COVID-19. JAMA 323: 1406-1407.

BANERJEE I, DOUAISI MP, MONDAL D & KANE RS. 2012. Light-activated nanotube–porphyrin conjugates as effective antiviral agents. Nanotechnology 23: 105101.

BARBETA VB, JARDIM RF, TORIKACHVILI MS, ESCOTE MT, CORDERO F, PONTES FM & TREQUATTRINI F. 2011. Metal-insulator transition in Nd 1− x Eu x NiO 3 probed by specific heat and anelastic measurements. J Appl Phys 109: 07E115.

BAUGHMAN RH, ZAKHIDOV AA & DE HEER WA. 2002. Carbon nanotubes - The route toward applications. Science 297: 787-792.

BIRD SW & KIRKEGAARD K. 2015. Escape of non-enveloped virus from intact cells. Virology 479-480: 444–449.

BÖHM S. 2014. Graphene against corrosion. Nat Nanotechnol 9: 741-742.

BORKOW G, ZHOU SS, PAGE T & GABBAY J. 2010. A Novel Anti-Influenza Copper Oxide Containing Respiratory Face Mask. PLoS ONE 5: e11295.

BRANDENBURG B & ZHUANG X. 2007. Virus trafficking - learning from single-virus tracking. Nat Rev Microbiol 5: 197-208.

BRITO AMM, BELLETI E, MENEZES LR, LANFREDI AJC & NANTES-CARDOS IL. 2019. Proteins and Peptides at the Interfaces of Nanostructures. An Acad Bras Cienc 91: e e20181236.

CAO YWC, JIN R & MIRKIN CA. 2002. Nanoparticles with Raman spectroscopic fingerprints for DNA and RNA detection. Science (80-) 297: 1536-1540.

CASTRO-MAYORGA JL, RANDAZZO W, FABRA MJ, LAGARON JM, AZNAR R & SÁNCHEZ G. 2017. Antiviral properties of silver nanoparticles against norovirus surrogates and their efficacy in coated polyhydroxyalkanoates systems. LWT - Food Sci Technol 79: 503-510.

CHAMPI A, AGUILAR AB, CAMILO M & QUINTANA M. 2016. Influence of the Iron Oxide Nanoparticles on the Electro-optical Properties of Graphite and Few-layers Graphene, p. S214-S220. Materials Today: Proceedings.

CHAN JFW, LAU SKP, TO KKW, CHENG VCC, WOO PCY & YUEN K-Y. 2015. Middle East Respiratory Syndrome Coronavirus: Another Zoonotic Betacoronavirus Causing SARS-Like Disease. Clin Microbiol Rev 28: 465-522.

CHAND S. 2000. Carbon fibers for composites. J Mater Sci 35: 1303-1313.

CHARRA F, GOTA-GOLDMANN S & WARLIMONT H. 2018. Nanostructured Materials, p. 1041-1080. In: Martienssen W (Ed). SPRINGER HANDBOOK OF MATERIALS DATA (Ed.). Springer Handbooks. Springer, Cham.

CHENG Y, LI D, JI B, SHI X & GAO H. 2010. Structure-based design of carbon nanotubes as HIV-1 protease inhibitors: Atomistic and coarse-grained simulations. J Mol Graph Model 29: 171-177.

CHIQUITO AJ, ESCOTE MT, ORLANDI MO, LANFREDI AJC, LEITE ER & LONGO E. 2007. Temperature dependence of electron properties of Sn doped nanobelts. Phys B Condens Matter 400: 243-247.

CIEJKA J, WOLSKI K, NOWAKOWSKA M, PYRC K & SZCZUBIAŁKA K. 2017. Biopolymeric nano/microspheres for selective and reversible adsorption of coronaviruses. Mater Sci Eng C 76: 735-742.

CRUZ GF, TOFANELLO A, ARAÚJO JN, NANTES-CARDOSO IL, FERREIRA FF & GARCIA W. 2018. Fast One-Pot Photosynthesis of Plasmonic Protein-Coated Silver/Silver Bromide Nanoparticles with Efficient Photocatalytic Performance. J Inorg Organomet Polym Mater 28: 2056-2062.

D'AMORA M & GIORDANI S. 2018. Carbon Nanomaterials for Nanomedicine, p. 103-113. Smart Nanoparticles for Biomedicine. Elsevier.

DE SOUZA JCP, IOST RM & CRESPILHO FN. 2016. Nitrated carbon nanoblisters for high-performance glucose dehydrogenase bioanodes. Biosens Bioelectron 77: 860-865.

DE VOLDER MFL, TAWFICK SH, BAUGHMAN RH & HART AJ. 2013. Carbon Nanotubes: Present and Future Commercial Applications. Science 339: 535-539.

DIAS CFB ET AL. 2012. Photo-induced electron transfer in supramolecular materials of titania nanostructures and cytochrome c. RSC Adv 2: 7417-7426.

DIZAJ SM, MENNATI A, JAFARI S, KHEZRI K & ADIBKIA K. 2015. Antimicrobial activity of carbon-based nanoparticles. Adv Pharm Bull 5: 19-23.

DONG X, LIANG W, MEZIANI MJ, SUN Y-P & YANG L. 2020. Carbon Dots as Potent Antimicrobial Agents. Theranostics 10: 671-686.

DRNDIĆ M. 2014. Sequencing with graphene pores. Nat Nanotechnol 9: 743-743.

DUHAN JS, KUMAR R, KUMAR N, KAUR P, NEHRA K & DUHAN S. 2017. Nanotechnology: The new perspective in precision agriculture. Biotechnol Reports 15: 11-23.

EL-SAYED IH, HUANG X & EL-SAYED MA. 2006. Selective laser photo-thermal therapy of epithelial carcinoma using anti-EGFR antibody conjugated gold nanoparticles. Cancer Lett 239: 129-135.

ELLIS BRADTB. 2009. The enigma of yellow fever in East Africa. Rev Med Virol 19: 57-64.

ESTEVAM ML, NASCIMENTO OR, BAPTISTA MS, DI MASCIO P, PRADO FM, FALJONI-ALARIO A, DO ROSARIO ZUCCHI M & NANTES IL. 2004. Changes in the spin state and reactivity of cytochrome c induced by photochemically generated singlet oxygen and free radicals. J Biol Chem 279: 39214-39222.

FERDOUS Z & NEMMAR A. 2020. Health impact of silver nanoparticles: A review of the biodistribution and

toxicity following various routes of exposure. Int J Mol Sci 21: 2375.

FERNANDO KAS, SAHU S, LIU Y, LEWIS WK, GULIANTS EA, JAFARIYAN A, WANG P, BUNKER CE & SUN YP. 2015. Carbon quantum dots and applications in photocatalytic energy conversion. ACS Appl Mater Interfaces 7: 8363-8376.

FERREIRA H, POMA G, ACOSTA DR, BARZOLA-QUIQUIA J, QUINTANA M, BARRETO L & CHAMPI A. 2018. Laser power influence on Raman spectra of multilayer graphene, multilayer graphene oxide and reduced multilayer graphene oxide, p. 012020. Journal of Physics: Conference Series. Institute of Physics Publishing.

FIRQUET S, BEAUJARD S, LOBERT PE, SANÉ F, CALOONE D, IZARD D & HOBER D. 2015. Survival of enveloped and non-enveloped viruses on inanimate surfaces. Microbes Environ 30: 140-144.

GADKARI RR, WAZED ALI S, DAS A & ALAGIRUSAMY R. 2020. Nanoparticles: a novel use in bioactive textiles, p. 297-306. Handbook of Nanomaterials for Manufacturing Applications. Elsevier.

GIRALDI TR, LANFREDI AJC, LEITE ER, ESCOTE MT, LONGO E, VARELA JA, RIBEIRO C & CHIQUITO AJ. 2007. Electrical characterization of SnO[sub 2]:Sb ultrathin films obtained by controlled thickness deposition. J Appl Phys 102: 034312.

GLEBOV OO. 2020. Understanding SARS-CoV-2 endocytosis for COVID-19 drug repurposing. FEBS J 287: 3664-3671.

GLEITER H. 2000. Nanostructured materials: basic concepts and microstructure. Acta Mater 48: 1-29.

GONZÁLEZ-BÉJAR M, PETERS K, HALLETT-TAPLEY GL, GRENIER M & SCAIANO JC. 2013. Rapid one-pot propargylamine synthesis by plasmon mediated catalysis with gold nanoparticles on ZnO under ambient conditions. Chem Commun 49: 1732-1734.

GONZALEZ N & JOHNSTON L. 2018. Safety of Engineered Nanomaterials. Chem Int 40: 28-29. https://doi.org/10.1515/ci-2018-0415.

HA MK, TRINH TX, CHOI JS, MAULINA D, BYUN HG & YOON TH. 2018. Toxicity Classification of Oxide Nanomaterials: Effects of Data Gap Filling and PChem Score-based Screening Approaches. Sci Rep 8: 3141.

HADRUP N, SHARMA AK, LOESCHNER K & JACOBSEN NR. 2020. Pulmonary toxicity of silver vapours, nanoparticles and fine dusts: A review. Regul Toxicol Pharmacol 115: 104690.

HE W, WU H, WAMER WG, KIM HK, ZHENG J, JIA H, ZHENG Z & YIN JJ. 2014. Unraveling the enhanced photocatalytic activity and phototoxicity of ZnO/metal hybrid nanostructures from generation of reactive oxygen species and charge carriers. ACS Appl Mater Interfaces 6: 15527-15535.

HODEK J, ZAJÍCOVÁ V, LOVETINSKÁ-ŠLAMBOROVÁ I, STIBOR I, MÜLLEROVÁ J & WEBER J. 2016. Protective hybrid coating containing silver, copper and zinc cations effective against human immunodeficiency virus and other enveloped viruses. BMC Microbiol 16: 1-12.

HOLZINGER M, GOFF ALE & COSNIER S. 2014. Nanomaterials for biosensing applications: A review. Front Chem 2: 1-10.

HUANG S ET AL. 2019. Benzoxazine monomer derived carbon dots as a broad-spectrum agent to block viral infectivity. J Colloid Interface Sci 542: 198-206.

JANA J, GANGULY M & PAL T. 2016. Enlightening surface plasmon resonance effect of metal nanoparticles for practical spectroscopic application. RSC Adv 6: 86174-86211.

JARDIM RF, BARBETA VB, ANDRADE S, ESCOTE MT, CORDERO F & TORIKACHVILI MS. 2015. Metal-insulator transition in Nd 1− x Eu x NiO 3: Entropy change and electronic delocalization. J Appl Phys 117: 17C105.

JIANG S, SHI Z, SHU Y, SONG J, GAO GF, TAN W & GUO D. 2020. A distinct name is needed for the new coronavirus. Lancet (London, England) 395: 949. Elsevier Ltd.

JOSHI M & BHATTACHARYYA A. 2011. Nanotechnology – a new route to high-performance functional textiles. Text Prog 43: 155-233.

KABB CP, CARMEAN RN & SUMERLIN BS. 2015. Probing the surface-localized hyperthermia of gold nanoparticles in a microwave field using polymeric thermometers. Chem Sci 6: 5662-5669.

KAROUSIS N, SUAREZ-MARTINEZ I, EWELS CP & TAGMATARCHIS N. 2016. Structure, Properties, Functionalization, and Applications of Carbon Nanohorns. Chem Rev 116: 4850-4883.

KHOLMANOV IN ET AL. 2012. Nanostructured Hybrid Transparent Conductive Films with Antibacterial Properties. ACS Nano 6: 5157-5163.

KOEHLER M, DELGUSTE M, SIEBEN C, GILLET L & ALSTEENS D. 2020. Initial Step of Virus Entry: Virion Binding to Cell-Surface Glycans. Annu Rev Virol 7: annurev-virology-122019-070025.

KOSTARELOS K & NOVOSELOV KS. 2014. Graphene devices for life. Nat Nanotechnol 9: 744-745.

KUKOVECZ Á, KOZMA G & KÓNYA Z. 2013. Multi-Walled Carbon Nanotube, p. 147-188. Springer Handbook of Nanomaterials. Berlin, Heidelberg: Springer Berlin Heidelberg.

KUMAR MISHRA S, SINGH P & RATH SK. 2013. Protective Effect of Quercetin on Chloroquine-Induced Oxidative Stress and Hepatotoxicity in Mice. Malar Res Treat 2013: 1-10.

KUMAR R ET AL. 2019. Iron oxide nanoparticles based antiviral activity of H1N1 influenza A virus. J Infect Chemother 25: 325-329.

LAM CW, JAMES JT, MCCLUSKEY R, AREPALLI S & HUNTER RL. 2006. A review of carbon nanotube toxicity and assessment of potential occupational and environmental health risks. Crit Rev Toxicol 36: 189-217.

LARA HH, AYALA-NUÑEZ NV, IXTEPAN-TURRENT L & RODRIGUEZ-PADILLA C. 2010. Mode of antiviral action of silver nanoparticles against HIV-1. J Nanobiotechnology 8: 1-10.

LARA HH, GARZA-TREVIÑO EN, IXTEPAN-TURRENT L & SINGH DK. 2011. Silver nanoparticles are broad-spectrum bactericidal and virucidal compounds. J Nanobiotechnology 9: 2-9.

LE PAPE H, SOLANO-SERENA F, CONTINI P, DEVILLERS C, MAFTAH A & LEPRAT P. 2002. Evaluation of the anti-microbial properties of an activated carbon fibre supporting silver using a dynamic method. Carbon N Y 40: 2947-2954.

LIM SY, SHEN W & GAO Z. 2015. Carbon quantum dots and their applications. Chem Soc Rev 44: 362-381.

LIU R, LIU HH, JI Z, CHANG CH, XIA T, NEL AE & COHEN Y. 2015. Evaluation of Toxicity Ranking for Metal Oxide Nanoparticles via an in Vitro Dosimetry Model. ACS Nano 9: 9303-9313.

LIU Y, GAYLE AA, WILDER-SMITH A & ROCKLÖV J. 2020. The reproductive number of COVID-19 is higher compared to SARS coronavirus. J Travel Med 27: 1-4.

LIU Y, ZHANG C & ZHANG X. 2018. Design, Fabrication and Application of Multi-Scale, Multi- Functional Nanostructured Carbon Fibers, p. 33-49. Recent Developments in the Field of Carbon Fibers. InTech.

LUXTON GWG, LEE JI-H, HAVERLOCK-MOYNS S, SCHOBER JM & SMITH GA. 2006. The Pseudorabies Virus VP1/2 Tegument Protein Is Required for Intracellular Capsid Transport. J Virol 80: 201-209.

MACYK W, JANCZYK A, KRAKOWSKA E & STOCHEL G. 2006. Singlet Oxygen Photogeneration at Surface Modified Titanium Dioxide. J Am Chem Soc 128: 15574-15575.

MAHMOUD IS, JARRAR YB, ALSHAER W & ISMAIL S. 2020. SARS-CoV-2 entry in host cells-multiple targets for treatment and prevention. Biochimie 175: 93-98.

MARSH M & HELENIUS A. 2006. Virus Entry: Open Sesame. Cell 124: 729-740. Cell Press.

MEDINA MS, BERNARDI JC, ZENATTI A & ESCOTE MT. 2020a. A new approach to obtain calcium cobalt oxide by microwave-assisted hydrothermal synthesis. Ceram Int 46: 1596-1600.

MEDINA MS, ZENATTI A & ESCOTE MT. 2020b. Fast Synthesis of Co 3 O 4 by Microwave-Assisted Hydrothermal Treatment. J Nanomater 2020: 1-8.

MENEZES LR, LOPES DM, BRONZATO JD, SOMBRIO G, CRIADO D, ZUNIGA A, LANFREDI AJC, SOUZA JA & NANTES-CARDOSO IL. 2019. Photo-induced Electron Transfer from Hematite and Zinc Oxide Nanostructures to Cytochrome C: Systems Applicable to Spintronics, p. 1-9. 2019 IEEE 9th International Nanoelectronics Conferences (INEC). IEEE.

MENEZES LR, SOMBRIO G, COSTA CA, BRONZATO JD, RODRIGUES T, SOUZA JA & NANTES-CARDOSO IL. 2020. Nanostructured Hematite Decorated with Gold Nanoparticles for Functionalization and Biocompatibility. Phys Status Solidi Appl Mater Sci 217: 1900589.

MIRANDA ÉGA ET AL. 2016. Effects of Gold Salt Speciation and Structure of Human and Bovine Serum Albumins on the Synthesis and Stability of Gold Nanostructures. Front Chem 4: 1-13.

MIYAKO E, NAGATA H, HIRANO K, SAKAMOTO K, MAKITA Y, NAKAYAMA K & HIROTSU T. 2008. Photoinduced antiviral carbon nanohorns. Nanotechnology 19: 075106.

MU Y ET AL. 2016. Predicting toxic potencies of metal oxide nanoparticles by means of nano-QSARs. Nanotoxicology 10: 1207-1214.

NAKANO R, ISHIGURO H, YAO Y, KAJIOKA J, FUJISHIMA A, SUNADA K, MINOSHIMA M, HASHIMOTO K & KUBOTA Y. 2012. Photocatalytic inactivation of influenza virus by titanium dioxide thin film. Photochem Photobiol Sci 11: 1293.

NANOT S, THOMPSON NA, KIM J-H, WANG X, RICE WD, HÁROZ EH, GANESAN Y, PINT CL & KONO J. 2013. Single-Walled Carbon Nanotubes, p. 105-146. Springer Handbook of Nanomaterials. Berlin, Heidelberg: Springer Berlin Heidelberg.

NANTES-CARDOSO & TOFANELLO DE SOUZA AI. 2019. Processo de síntese verde simultânea de nanopartículas metálicas e magnéticas com uso de proteínas armazenadoras de ferro. BR1020190158.

NIETO-JUAREZ JI & KOHN T. 2013. Virus removal and inactivation by iron (hydr)oxide-mediated Fenton-like processes under sunlight and in the dark. Photochem Photobiol Sci 12: 1596.

NOVOSELOV KS. 2004. Electric Field Effect in Atomically Thin Carbon Films. Science 306: 666-669.

PEDROSA M, SAMPAIO MJ, HORVAT T, NUNES OC, DRAŽIĆ G, RODRIGUES AE, FIGUEIREDO JL, SILVA CG, SILVA AMT & FARIA JL. 2019. Visible-light-induced self-cleaning functional fabrics using graphene oxide/carbon nitride materials. Appl Surf Sci 497: 143757.

PEÑA-BAHAMONDE J, NGUYEN HN, FANOURAKIS SK & RODRIGUES DF. 2018. Recent advances in graphene-based biosensor technology with applications in life sciences. J Nanobiotechnology 16: 1-17.

PERREAULT F, DE FARIA AF, NEJATI S & ELIMELECH M. 2015. Antimicrobial Properties of Graphene Oxide Nanosheets: Why Size Matters. ACS Nano 9: 7226-7236.

POCHKAEVA EI ET AL. 2020. Fullerene derivatives with amino acids, peptides and proteins: From synthesis to biomedical application. Prog Solid State Chem 57: 100255.

POMAR CD, MARTINHO H, FERREIRA FF, GOIA TS, RODAS ACD, SANTOS SF & SOUZA JA. 2018. Synthesis of magnetic microtubes decorated with nanowires and cells. AIP Adv 8: 045008.

PUZYN T, RASULEV B, GAJEWICZ A, HU X, DASARI TP, MICHALKOVA A, HWANG HM, TOROPOV A, LESZCZYNSKA D & LESZCZYNSKI J. 2011. Using nano-QSAR to predict the cytotoxicity of metal oxide nanoparticles. Nat Nanotechnol 6: 175-178.

RAHAMAN MS, VECITIS CD & ELIMELECH M. 2012. Electrochemical carbon-nanotube filter performance toward virus removal and inactivation in the presence of natural organic matter. Environ Sci Technol 46: 1556-1564.

RAO MV, RAJESHWAR K, PAL VERNEKER VR & DUBOW J. 1980. Photosynthetic production of H2 and H2O2 on semiconducting oxide grains in aqueous solutions. J Phys Chem 84: 1987-1991.

RASHID JIA & YUSOF NA. 2017. The strategies of DNA immobilization and hybridization detection mechanism in the construction of electrochemical DNA sensor: A review. Sens Bio-Sensing Res 16: 19-31.

RIEDINGER A, GUARDIA P, CURCIO A, GARCIA MA, CINGOLANI R, MANNA L & PELLEGRINO T. 2013. Subnanometer local temperature probing and remotely controlled drug release based on Azo-functionalized iron oxide nanoparticles. Nano Lett 13: 2399-2406.

RIETDORF J, PLOUBIDOU A, RECKMANN I, HOLMSTRÖM A, FRISCHKNECHT F, ZETTL M, ZIMMERMANN T & WAY M. 2001. Kinesin-dependent movement on microtubules precedes actin-based motility of vaccinia virus. Nat Cell Biol 3: 992-1000.

RODRIGUES T, DE FRANÇA LP, KAWAI C, DE FARIA PA, MUGNOL KCU, BRAGA FM, TERSARIOL ILS, SMAILI SS & NANTES IL. 2007. Protective role of mitochondrial unsaturated lipids on the preservation of the apoptotic ability of cytochrome c exposed to singlet oxygen. J Biol Chem 282: 25577-25587.

RODUNER E. 2006. Size matters: Why nanomaterials are different. Chem Soc Rev 35: 583-592.

RUALES-LONFAT C, BARONA JF, SIENKIEWICZ A, BENSIMON M, VÉLEZ-COLMENARES J, BENÍTEZ N & PULGARÍN C. 2015. Iron oxides semiconductors are efficients for solar water disinfection: A comparison with photo-Fenton processes at neutral pH. Appl Catal B Environ 166-167: 497-508.

SANG X, PHAN TG, SUGIHARA S, YAGYU F, OKITSU S, MANEEKARN N, MÜLLER WEG & USHIJIMA H. 2007. Photocatalytic inactivation of diarrheal viruses by visible-light-catalytic titanium dioxide. Clin Lab 53: 413-421.

SANTOS HF, DOS SANTOS CG, NASCIMENTO OR, REIS AKCA, LANFREDI AJC, DE OLIVEIRA HPM & NANTES-CARDOSO IL. 2020. Charge separation of photosensitized phenothiazines for applications in catalysis and nanotechnology. Dye Pigment 177: 108314.

SCHNORR JM & SWAGER TM. 2011. Emerging Applications of Carbon Nanotubes. Chem Mater 23: 646-657.

SIMONCIC B & TOMSIC B. 2010. Structures of Novel Antimicrobial Agents for Textiles - A Review. Text Res J 80: 1721-1737.

SINGH AV, LAUX P, LUCH A, SUDRIK C, WIEHR S, WILD A-M, SANTOMAURO G, BILL J & SITTI M. 2019. Review of emerging concepts in nanotoxicology: opportunities and challenges for safer nanomaterial design. Toxicol Mech Methods 29: 378-387.

SIOCHI EJ. 2014. Graphene in the sky and beyond. Nat Nanotechnol 9: 745-747.

SPORTELLI MC, IZZI M, KUKUSHKINA EA, HOSSAIN SI, PICCA RA, DITARANTO N & CIOFF N. 2020. Can nanotechnology and materials science help the fight against sars-cov-2? Nanomaterials 10: 802.

STARING J, RAABEN M & BRUMMELKAMP TR. 2018. Viral escape from endosomes and host detection at a glance. J Cell Sci 131: 1-8.

STEINHART M. 2004. Introduction to Nanotechnology. By Charles P. Poole, Jr. and Frank J. Owens. Angew Chemie Int Ed 43: 2196-2197. Wiley.

STROM TA, DURDAGI S, ERSOZ SS, SALMAS RE, SUPURAN CT & BARRON AR. 2015. Fullerene-based inhibitors of HIV-1 protease. J Pept Sci 21: 862-870.

SUN YP, FU K, LIN Y & HUANG W. 2002. Functionalized carbon nanotubes: Properties and applications. Acc Chem Res 35: 1096-1104.

THEEK B, RIZZO LY, EHLING J, KIESSLING F & LAMMERS T. 2014. The theranostic path to personalized nanomedicine. Clin Transl Imaging 2: 67-76.

TOFANELLO A, MIRANDA ÉGA, DIAS IWR, LANFREDI AJC, ARANTES JT, JULIANO MA & NANTES IL. 2016. PH-Dependent Synthesis of Anisotropic Gold Nanostructures by Bioinspired Cysteine-Containing Peptides. ACS Omega 1: 424-434.

TOFIGHY MA & MOHAMMADI T. 2019. Barrier, diffusion, and transport properties of rubber nanocomposites containing carbon nanofillers, p. 253-285. Carbon-Based Nanofillers and Their Rubber Nanocomposites: Fundamentals and Applications. Elsevier.

TORRISI F & COLEMAN JN. 2014. Electrifying inks with 2D materials. Nat Nanotechnol 9: 738-739.

TORTELLA GR, RUBILAR O, DURÁN N, DIEZ MC, MARTÍNEZ M, PARADA J & SEABRA AB. 2020. Silver nanoparticles: Toxicity in model organisms as an overview of its hazard for human health and the environment. J Hazard Mater 390: 121974.

VAN DOREMALEN N ET AL. 2020. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. N Engl J Med 382: 1564-1567.

VECITIS CD, SCHNOOR MH, RAHAMAN MS, SCHIFFMAN JD & ELIMELECH M. 2011. Electrochemical multiwalled carbon nanotube filter for viral and bacterial removal and inactivation. Environ Sci Technol 48: 3672-3679.

WALTERS C, POOL E & SOMERSET V. 2016. Nanotoxicology: A Review, p. 45-63. Toxicology - New Aspects to This Scientific Conundrum. InTech.

WAN Y, SHANG J, GRAHAM R, BARIC RS & LI F. 2020. Receptor Recognition by the Novel Coronavirus from Wuhan: an Analysis Based on Decade-Long Structural Studies of SARS Coronavirus. J Virol 94: 127-147. American Society for Microbiology.

WANG Y & HU A. 2014. Carbon quantum dots: Synthesis, properties and applications. J Mater Chem C 2: 6921-6939.

WARNES SL, LITTLE ZR & KEEVIL CW. 2015. Human coronavirus 229E remains infectious on common touch surface materials. MBio 6: 1-10.

YAN G, CHEN J & HUA Z. 2009. Roles of H2O2 and OH{radical dot} radical in bactericidal action of immobilized TiO2 thin-film reactor: An ESR study. J Photochem Photobiol A Chem 207: 153-159.

YANG SY ET AL. 2010. Magnetically enhanced high-specificity virus detection using bio-activated magnetic nanoparticles with antibodies as labeling markers. J Virol Methods 164: 14-18.

YE S, SHAO K, LI Z, GUO N, ZUO Y, LI Q, LU Z, CHEN L, HE Q & HAN H. 2015. Antiviral Activity of Graphene Oxide: How Sharp Edged Structure and Charge Matter. ACS Appl Mater Interfaces 7: 21578-21579.

ZAICHICK S V, BOHANNON KP, HUGHES A, SOLLARS PJ, PICKARD GE & SMITH GA. 2013. The herpesvirus VP1/2 protein is an effector of dynein-mediated capsid transport and neuroinvasion. Cell Host Microbe 13: 193-203.

ZEEDAN GSG, ABD EL-RAZIK KA, ALLAM AM, ABDALHAMED AM & ABOU ZEINA HA. 2020. Evaluations of potential antiviral effects of green zinc oxide and silver nanoparticles against bovine herpesvirus-1. Adv Anim Vet Sci 8: 433-443.

ZENATTI A, REY JFQ, LANFREDI AC, LEITE ER, LONGO E & ESCOTE MT. 2013. LaNiO 3 Nanotubes Produced Using a Template-Assisted Method. J Nanosci Nanotechnol 13: 1-6.

ZHANG Z, HAN S, WANG C, LI J & XU G. 2015. Single-walled carbon nanohorns for energy applications. Nanomaterials 5: 1732-1755.

ZHI M, XIANG C, LI J, LI M & WU N. 2013. Nanostructured carbon–metal oxide composite electrodes for supercapacitors: a review. Nanoscale 5: 72-88.

ZHOU K, ZHU Y, YANG X & LI C. 2010. One-pot preparation of graphene/Fe3O4 composites by a solvothermal reaction. New J Chem 34: 2950-2955.

ZHU S & XU G. 2010. Single-walled carbon nanohorns and their applications. Nanoscale 2: 2538-2549.

How to cite

TOLEDO GG, TOLEDO VH, LANFREDI AJC, ESCOTE M, CHAMPI A, SILVA MCC & NANTES-CARDOSO IL. 2020. Promising Nanostructured Materials against Enveloped Virus. An Acad Bras Cienc 92: e20200718. DOI 10.1590/0001-3765202020200718.

Manuscript received on May 11, 2020;
accepted for publication on September 18, 2020

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