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REVIEW

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Beyond superconductivity towards novel biomedical, energy, ecology, and heritage applications of MgB_2

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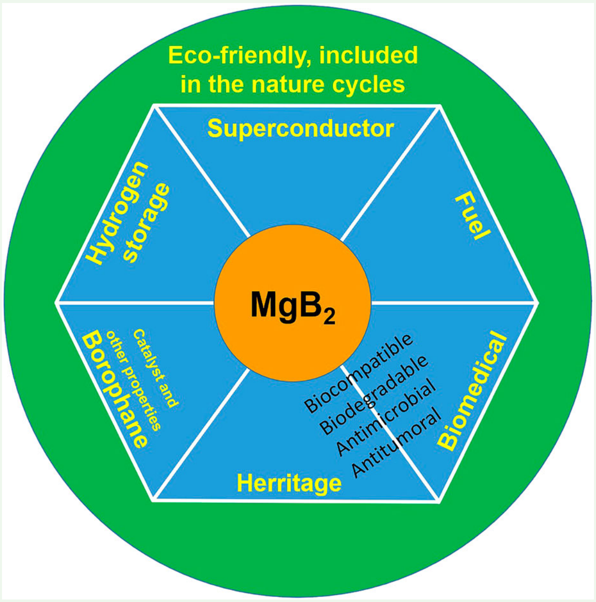
ABSTRACT
Twenty years passed since the discovery of superconductivity in MgB_2. Although there is much progress, the use of superconductors, in general, and of MgB_2 in particular, remains limited. On the other hand, in the last 10 years MgB_2 became a material of great interest for emergent applications, such as propellants, batteries, and catalysis, as a source material to obtain 2D borophene-like materials (e.g. BH borophane), biomedical field (taking advantage of its promising antimicrobial, antitumoral, biodegradable, and biocompatible features), heritage and ecology being the latest trends. These new directions place MgB_2 as a material well integrated with nature cycles that can promote the concept of one eco- and health-friendly, with many envisioned practical purposes. This type of material is at the core of a clean and sustainable economy promoting new developments, boosting the older ones (e.g. superconductivity) and minimizing the costs for the transition to new and modern materials and technologies. In this work, we review recent trends and new directions of MgB_2 applications and discuss their potential impact.



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1. Impact of materials today and MgB_2

One materials classification is based on their targeted practical application or function, e.g. materials specifically designed for power and energy, electronics, aerospace, transportation, medicine, sports, and construction. The limitation is that aiming for a specific technical or technological solution, materials, and technologies are unilaterally optimized for one application. Few parameters, such as efficiency or efficiency per cost are defined as the key indicators of success. There are also other

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important aspects. Implications of indirect and long-term impact of materials and technologies on nature, especially on the biosphere, are difficult to identify, anticipate, and quantify for the whole spectrum of materials: the impact is in fact resumed to their influence on nature cycles, on equilibrium, and on time dependent balancing mechanisms. The required time for adaptation to the new conditions induced by using new materials must match the time scale of the inevitable changes. A human being is known as the most invasive species, and many recently developed materials, initially considered nature friendly, are now suffocating nature. This is not a trivial aspect, and we can already see new measures and laws for avoiding catastrophic changes (such as air, water, and soil pollution, global warming, etc.). These changes are life threatening and are leading to the extinction of many climate/pollutions sensitive species because of the rapid climate change and/or pollution increase. More and more, public voices and governments promote and apply the principles of healthy human life and activity, where eco-friendly, green materials play a major role. In industrial design, there are already examples of software tools for generative design based on artificial intelligence or for smart selection of materials based on their both ecological and economic impacts. Many materials are currently defined by a low carbon footprint, energy cost, water consumption, pollution, and recycling, to provide a low contribution to global warming. It means that through fabrication technology and use they do not produce high emissions of greenhouse gases over a long enough timeframe, allowing the biosphere to smoothly adapt without extreme response, even if the materials are not recycled. These materials are integrated and are usually derived from nature. Examples are ceramics and glass made of natural minerals, materials produced from natural or agricultural products such as plants and animals, or artificial materials that replicate the natural ones or react to environment in a similar manner. According to their destination, these friendly materials are labeled as biodegradable, recyclable, safe, non-toxic, biocompatible, etc.

Under the presented circumstances, how shall the materials of the future be designed? This question may raise different answers. In the view of the previous paragraph, materials stronger connected and integrated with cycles of the nature and biosphere are seen as an advantage over the others, but is this enough? Unfortunately, these materials cannot ensure fast enough progress, and cannot replace already successful materials used in high-tech applications, indispensable today. For the progress of the future society, game-changing materials are required. History shows periods defined by materials, e.g. stone, bronze, iron, aluminum, plastics, and silicon ages (though other materials were used as well).

Energy materials deserve special attention since they are at the core of any human activity. One of the main challenges, according to the present concerns, is their high CO_2 footprint. From a larger perspective, they are in fact far away from the nature cycles, energy, and time scales of these processes. For example, fuel or a power generating device should be as compact as possible, to deal with as much as possible energy, and release/absorb/store/transport the energy within a certain time frame. Although this is common sense, there is no clear understanding of the consequences and impact on nature cycles. For example, solar and wind generation technologies labeled as ecofriendly already start to show different problems in near future recycling (*1*). One reasonable question is how long it will take to replace all fossil fuels and reach a carbon-free state? At that point, we may assume a carbon zero or/and a close to 100% renewable industry. In fact, the immediate solution found under a certain pressure usually creates a new problem. Recent natural disasters or human conflicts have pointed to the fact that the world is not fully prepared to give up fossil fuel. In extreme unforeseen situations of crisis, there is a strong drawback in clean energy use, e.g. with a reconsideration of coal-based energy production, even in countries with a strong green policy. Essential become questions regarding safety, security, independence, and reliability of the energy rather than pollution and principles of a clean environment.

The conflicting aspects and presented uncertainty of the progress outcome suggest we look for different, alternative solutions. These solutions should compensate for each other effects and bring the system of solutions closer to nature cycles, i.e. to a self-balancing and harmonious eco-social system. Currently, the hydrogen-based economy is highly regarded as the future of a clean economy. On the other hand, hydrogen, along with oxygen, carbon, and nitrogen are involved on a large scale in nature cycles, including those related to life. Where would be the balance, how to preserve it, how much hydrogen we need, or should we produce to minimize the current problem of greenhouse gases or avoid a new and similar one concerning hydrogen footprint? While the answer to these questions remains open for discussion, the diversity principle concerning materials deserves attention. This can be understood considering many different materials or just a few friendly materials, but with many functions.

In this work, we review MgB_2 as a case study of one material with different functions, already useful for energy and power applications, still well integrated

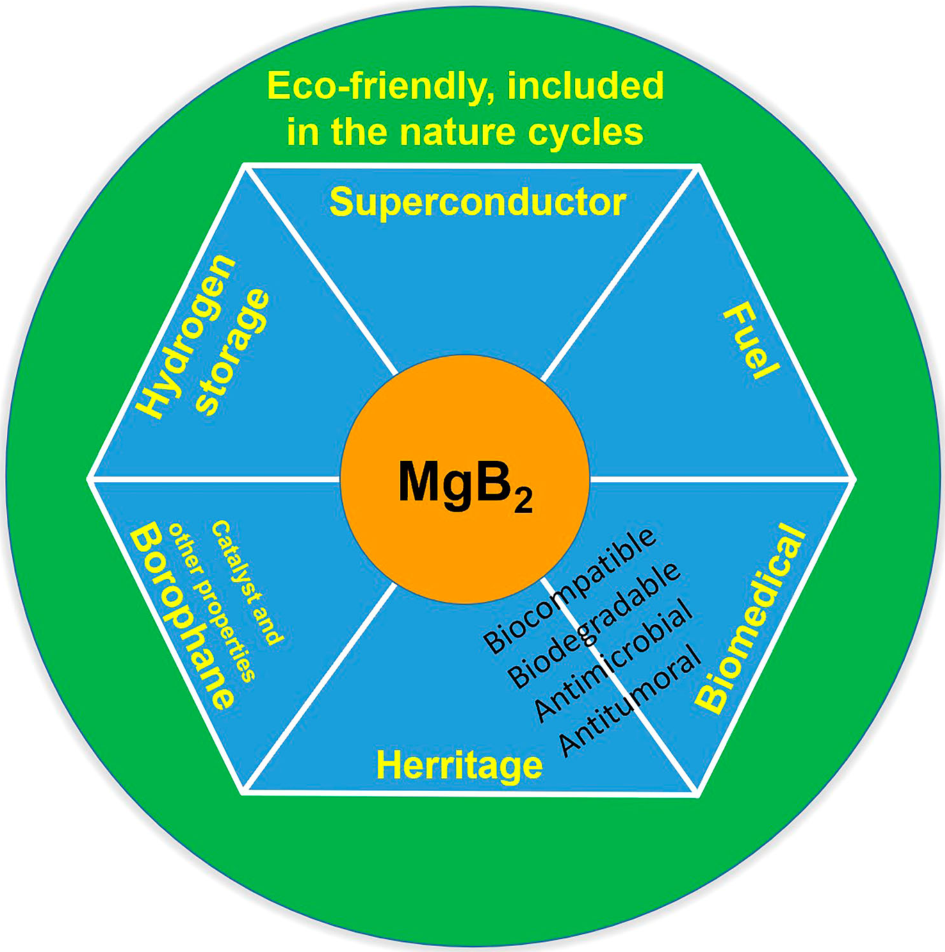

Figure 1. Emergent fields of MgB_2 applications and its impact.

into the nature cycles. Various functions are discussed emphasizing implications, future directions of research, and potential perspectives of the addressed concept (Figure 1).

2. MgB_2 a superconducting practical material

First attempts to obtain magnesium borides were reported in 1890 (Mg_9B_2, Mg_2B_5) (*2*) and in 1914 (Mg_3B_2) (*3*). In 1953 MgB_2 and MgB_4 were for the first time synthesized and based on X-Ray diffraction analysis (*4*) a hexagonal structure was identified, with lattice parameters $a = 3.084 \pm 0.001$ Å and $c = 3.522 \pm 0.002$ Å. MgB_2 has a 2D hexagonal layered crystal structure, where planes of B alternate with those of Mg. MgB_2 can be considered a borophene-like material intercalated with Mg-planes. It has metallic conductivity at room temperature, and in 2001 it was demonstrated that MgB_2 is a superconductor (*5*) with a critical temperature T_c of 39 K. This unexpectedly high T_c for a binary compound and other superconducting characteristics (large coherence length, relatively high critical current density, and high irreversibility field) promoted MgB_2 as a practical superconductor with high potential for industrial applications (*6*), e.g. in the energy and medical imaging sectors. Proposed products could efficiently work at temperatures up to 25–30 K. To achieve these temperatures the cooling agent can be H_2, with a boiling point at 20.28 K. This means that the envisioned hydrogen clean industry will easily accommodate and benefit from currently developing machines, devices, and equipment based on MgB_2 superconductor. MgB_2 is a lightweight material with a bulk density of 2.63 g/cm^3. It is the lightest material among practical superconductors. This makes MgB_2 attractive for portable applications (*6*). For example, MgB_2 shows excellent magnetic shielding properties (*7*) (Figure 2) that can be useful for passive shielding of devices and orbital stations, protecting them in space from cosmic radiation. Also, raw materials are largely available and do not contain rare earth, noble or toxic elements as in the case of other high- or low-temperature superconductors. The engineering properties of MgB_2 can be improved by additions.

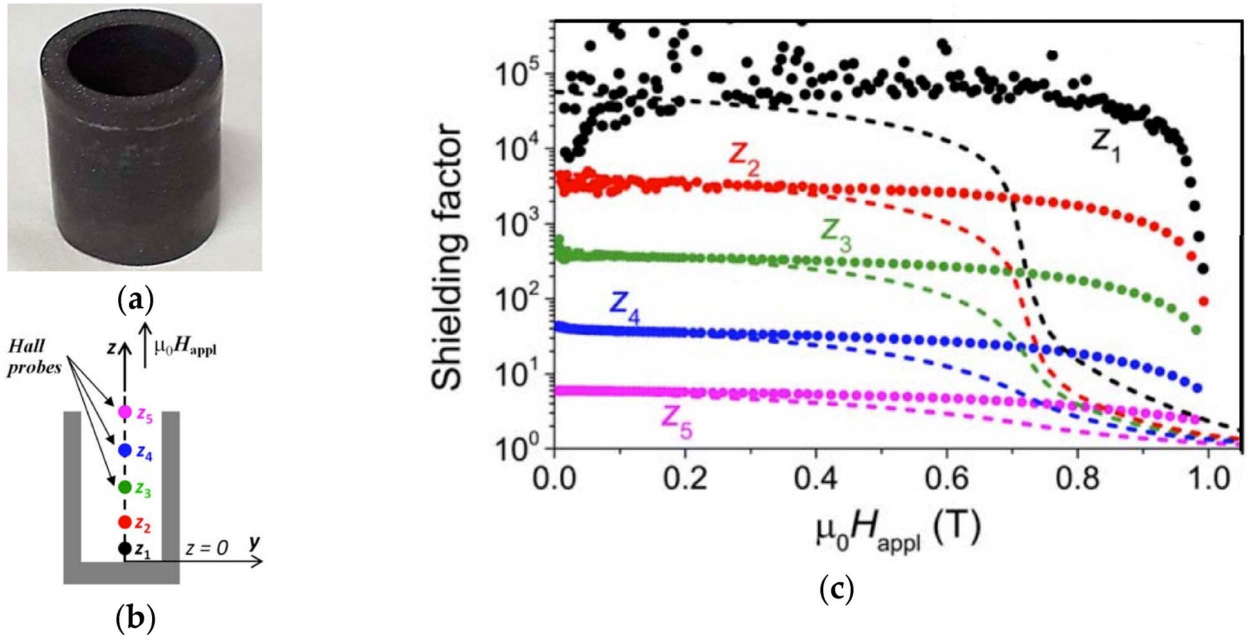

Figure 2. (a) Magnetic shield of MgB_2 added with hexagonal BN in the shape of a cup (outer radius, $R_o = 10.15$ mm, inner radius, $R_i = 7.0$ mm, external height, $h_e = 22.5$ mm, internal depth, $d_i = 18.3$ mm). The material is machinable by chipping; shielding factors (i.e. the ratio between outer applied magnetic field H_{appl} and inner magnetic field measured by a Hall sensor at different z_1–z_5 positions (b)) at $T = 30$ K are shown in (c). The dashed lines represent the shielding factors computed in correspondence of the Hall probe positions, assuming the $J_c(B)$ dependence at 30 K. Note very high shielding factors up to ∼0.8 T. Adapted from ref. (*7*).

Despite presented undeniable advantages and huge potential impacting virtually all industries and human society, applications based on MgB_2 and on other practical superconductors remain a high-tech niche without large-scale products. High costs prevent the development of superconductors and superconducting applications for general use. Enlarging the application range of superconductors, especially those that are bio-eco-friendly, by taking advantage of other properties than superconductivity may generate a new favorable environment for their use. This environment may boost indirectly superconducting applications, but, currently, an analysis is missing. As already pointed out, MgB_2 is notable for superconductivity. It is of much interest that other functions of MgB_2 were recently explored, and new applications emerged in the last years, the list being open for new ideas and development of applications.

3. MgB_2 as a propellant

In aerospace and underwater propulsion, MgB_2 can become of interest as a propellant. Both Mg and B have excellent gravimetric/volumetric calorific values (*8*) of 58.86 kJ·g^{-1}/137.73 kJ·cm^{-3}, and 24.70 kJ·g^{-1}/ 43.00 kJ·cm^{-3}, respectively. One observes that for B, the calorific values are higher than for Mg, but the presence of Mg in mixtures of Mg and B can promote ignition and combustion of B. Magnesium ignites first and increases the environment temperature to higher values necessary to induce the ignition of B. Stability of B ignition depends on its surface status, on the presence of oxides and other impurities, and the mixing level between B and Mg. To overcome these problems, it was proposed by Liang et al (*9*) to use MgB_2 as a propellant (38.5 kJ·g^{-1}) (*10*). It was found that MgB_2 has a shorter ignition time and longer stable combustion stage time than for Mg or B (Figure 3). Gunda et al (*11*) reported that MgB_2, as a catalytic and energetic additive, supports

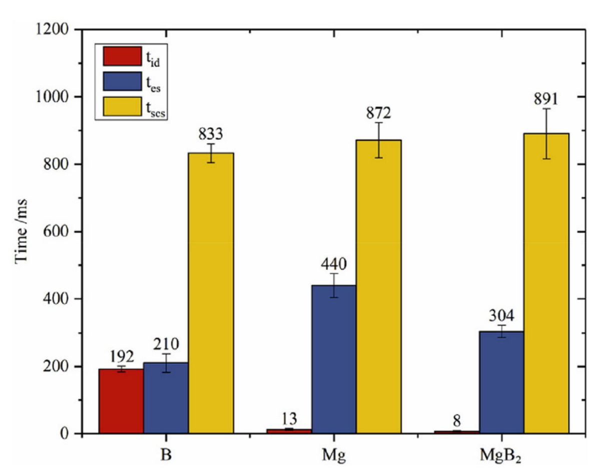

Figure 3. Ignition delay (t_{id}) and two-stage combustion (explosion, t_{es} and stable combustion, t_{scs}) times for B, Mg, and MgB_2 (from ref. (*9*)).

and enhances the thermal decomposition of ammonium perchlorate (NH_4ClO_4), a major ingredient in the currently used solid rocket propellants. Namely, the energy release is enhanced by 78% and the decomposition temperature is reduced by 73°C. MgB_2 was present in the boron fuel from the typical rocket propellant (*12*). Recently, MgB_2 was also used in green fireworks made of a MgB_2/$NaNO_2$-PVA composite (*13*).

4. MgB_2 for hydrogen storage and batteries

In the field of solid oxide fuel cells (SOFC) technology and batteries for electric cars and other applications, MgB_2 can also play an important role.

In the first case, hydrogen storage as fuel for SOFC is not a trivial problem. Severa et al. (*14*) reported more than 11 wt. % of reversible hydrogen storage by direct hydrogenation of MgB_2 to $Mg(BH_4)_2$ in at least 75% yield. Stepwise dehydrogenation takes place following reactions (1)–(3):

$$6Mg(BH_4)_2 \rightarrow 5MgH_2 + Mg(B_{12}H_{12}) + 13H_2 \quad (1)$$

$$5MgH_2 \rightarrow 5Mg + 5H_2 \quad (2)$$

$$5Mg + Mg(B_{12}H_{12}) \rightarrow 6MgB_2 + 6H_2 \quad (3)$$

Improved hydrogen storage properties of MgB_2 were obtained by surfactant (a mixture of heptane, oleic acid, and oleylamine) ball milling to produce a boron deficient powder product (*15*) with a plate-like morphology and particle sizes ranging from 5 to 50 nm.

Garapati and Sundara (*16*) used MgB_2 as a metallic interlayer at the nitrogen-doped highly porous carbon cathode with interconnected pores as the sulfur host (NC-S) in high-energy-density lithium–sulfur batteries for electric vehicles. This solution of an NC-S/MgB_2 cathode proved to deliver high specific capacity and rate capability, and excellent cyclic stability (Figure 4). Pang et al (*17*) have shown similar promising results in the case of lithium-sulfur batteries, where MgB_2 powder was introduced between graphene nanosheets to form the high surface-area composite of the sulfur cathode that achieved stable cycling at a high sulfur loading of 9.3 mg·cm^{-2}.

5. MgB_2 catalyst and water splitting

Photocatalytic properties of MgB_2 for water splitting were proved in ref. (*18*). Water splitting is unanimously recognized as environment friendly, potentially low cost and renewable energy solution in the future hydrogen economy. Authors demonstrate photogeneration under IR-VS light irradiation of the electric current from dissociated water molecules using MgB_2 as a catalyst with a conversion efficiency of ~27% at bias voltage V_{bias} = 0.5 V. Metal-doped (Fe, Co) MgB_2 works well also as an electrocatalyst (*19*), being a potential candidate to replace Pt-based catalysts involved in the hydrogen evolution reaction (HER) during water splitting (Figure 5).

6. MgB_2 as a precursor for obtaining 2D materials (nanosheets and borophane)

The reaction of MgB_2 with water (*20*) was studied in 2001. The main reaction products are $Mg(OH)_2$, B, and H_2 (gas).

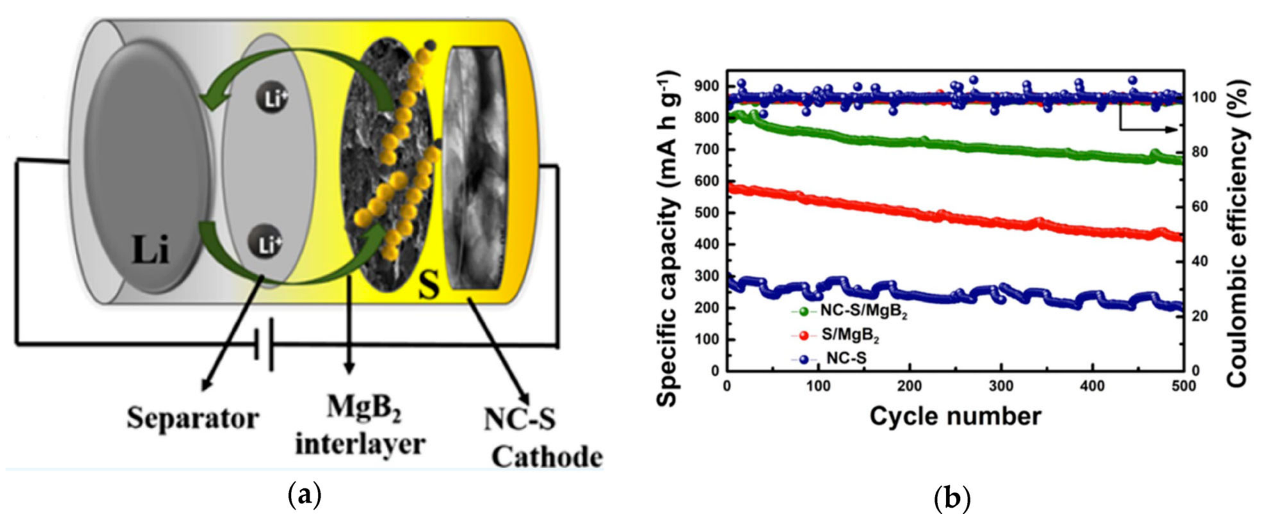

Figure 4. (a) Li-S battery for electric cars with MgB_2 interlayer; (b) the long-term cyclic stability of the NC-S, S/MgB_2, and NC-S/MgB_2 cathodes evaluated at 1 C rate in the potential window 2.8−1.7 V for 500 cycles. At the end of 500 cycles, cathodes NC-S (without interlayer), S/MgB_2, and NC-S/MgB_2 could retain 66.4%, 71%, and 85% (and ~99% of coulombic efficiency) of initial capacity, respectively. NC-S denotes nitrogen-doped highly porous carbon (NC) with interconnected pores as the sulfur (S) host (from ref. (*16*)).

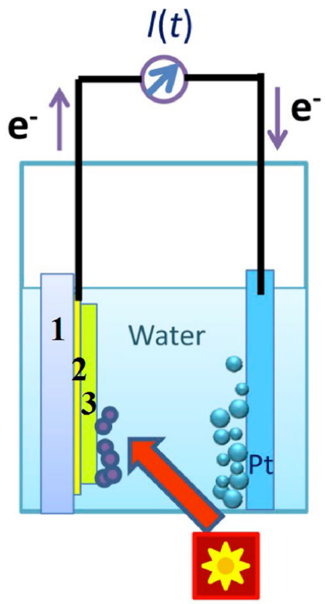

Figure 5. Photoelectrochemical cell using MgB_2 as the photoanode (1 – glass, 2 – Au, 3 – MgB_2) and Pt as the cathode in distilled water (from ref. (18)).

B_2O_3 and $MgCO_3$ were also detected by XPS on the sample's surface. Following the example of Mg and MgO behavior in water (21), one may expect that the degradation mechanism is more complex involving different steps and intermediate reaction products. Indeed, some recent experiments support this observation (22). Corrosion of MgB_2 is influenced in the aqueous physiological environment by preferential Mg reaction with anions (e.g. Cl, S, P) (23–25). In addition, the formation of low water-soluble $Mg(OH)_2$ can passivate the surface and hinder the reaction of MgB_2 with water, but the solubility of $Mg(OH)_2$ increases in the physiological environment (26). In a medium containing proteins, dissolution of Mg is suppressed (27). Interaction with water is also influenced by composition, morphological, and structural features (28). Although the pH values of different pristine MgB_2 powders in water saturated at ∼10, kinetics to reach saturation was different. By high energy sonication in water Das et al. (29) observed exfoliation into few-layer-thick Mg deficient hydroxyl-functionalized nanosheets. The chemically modified MgB_2 nanosheets show photoluminescence and low absorptivity (2.9 ml·mg^{-1}·cm^{-1} measured for an excitation wavelength $\lambda = 200$ nm) when compared with other 2D materials such as graphene, Mo_2S, h-BN, and WS_2. Photoluminescence was not observed in the parent MgB_2. The ability of MgB_2 to yield nanosheets by exfoliation with properties different than that of the parent material is considered to open multiple new perspectives in science and technology and to lay the foundations of other metal borides exfoliation. Further experiments on MgB_2 exfoliation and investigation of the products and their properties were performed in refs. (22, 30–35). In these articles hydrogen boride (HB) nanosheets, named also *borophane*, were synthesized (Figure 6). The treatment of MgB_2 was performed in acetonitrile or methanol with a proton-exchange resin, under an inert nitrogen atmosphere, at room temperature, and under ambient pressure. MgB_2 is stable in organic media such as ethanol, methanol, and acetone (36), and to enhance the yield in the exfoliation process through the exchange mechanism, formic acid was also added (35). The HB sheets were shown to exhibit acid catalytic activity promoting ethanol conversion into hydrocarbons (32), a property not found in the parent MgB_2. The HB nanosheets were also used as reductants of the metals with reduction potentials larger than −0.257 V versus standard hydrogen electrode (34). By this approach, HB-metal nanocomposites were obtained. The HB nanosheets release 8% of hydrogen under photoirradiation, indicating a high H_2-storage capacity (33), being comparable with that of the metal H_2 storage materials. Synthesis of borophane (HB) from magnesium boride is a remarkable continuation of

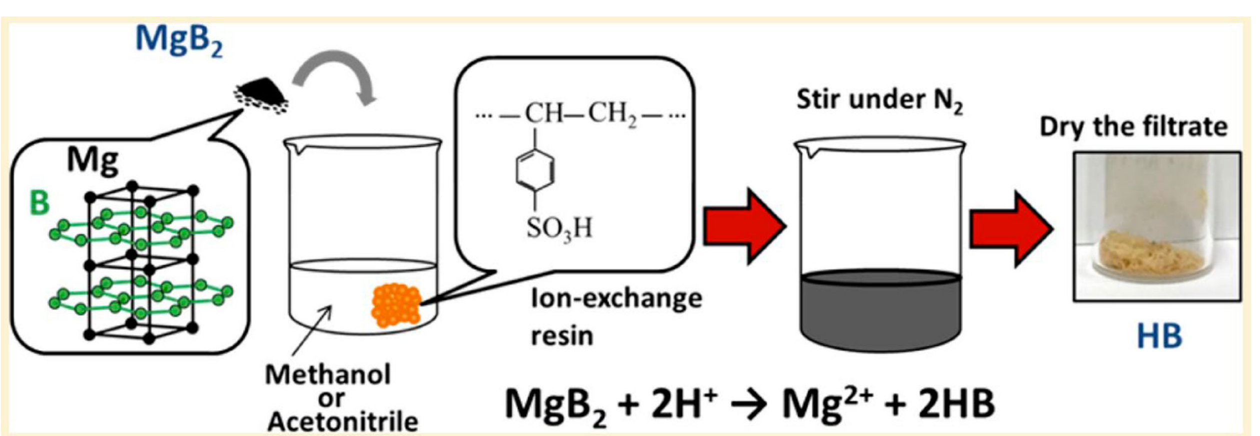

Figure 6. Synthesis of 2D borophane (HB) using MgB_2 as a precursor (from ref. (30)).

previous works to produce boride hydrides such as B_4H_{10} (*37*, *38*).

7. MgB_2 as a biodegradable, antibacterial, and biocompatible material used for biomedical applications

MgB_2 sparked not only catalysis and energy fields. MgB_2 as a biodegradable and biocompatible material can play an important role in bio, eco, medical, and other related fields.

The first article proposing the use of MgB_2 in the biomedical applications (*39*) was published in 2014. The biocompatibility of MgB_2 resides in the relatively high abundance and the important role played in humans, plants, and animals of the component elements. Mg and B are considered macronutrients and micronutrients (though quite close to the macronutrient region and approximately similar to Fe and Zn that are essential elements for life), respectively, with catalytic function in enzymatic reactions (*40*).

Mg and some Mg-alloys have shown excellent biocompatibility without symptoms of allergic or toxic reactions and safe degradation (*41–47*). The daily intake of Mg is 240–420 mg/day (*48*) and of B is 1–7 mg/day (*49*). In healthy people, boron levels (*50*) are 15-80 µg/kg. Boron is present in the body as boric acid, and it is completely absorbed from the gastrointestinal tract (*51*). Boron is involved in healthy bone growth and cell membrane care (*52–55*). However, as pointed out by Kot (*54*), information about the physiological functions of B is fragmentary and often contradictory, while little is known about B speciation of living matter-bearing formations, i.e. soils, natural waters, and sediments.

The *in vitro* cytotoxicity of MgB_2 powders on different cellular lines was studied and recently reported (*28*, *56*, *57*). While this is a useful information, in general, for Mg-based alloys it is recognized that dynamic effects are important, and only *in vivo* tests are relevant to observe if the body can accommodate the effects of the material implantation (*25*).

Promising results (*58*) were presented for nanosheets of MgB_2 used to induce hydrogen release at targeted gastric cancer cells (Figure 7). The approach opens a new treatment path, the hydrogen-chemotherapy of the digestive tumors, considered to induce reduced toxic side effects compared to ordinary chemotherapy. *In vitro* experiments on cervical and colon tumor cells (lines HeLa and HT-29) have also demonstrated excellent activity (*28*) of MgB_2. Experiments of the cellular cycle revealed that the MgB_2 powders mainly induce apoptosis and arrest of the tested tumor cells in the S phase: they interfere with DNA synthesis and cellular proliferation. MgB_2 was introduced in mice and remarkable changes in the intestinal microbiota were observed. Microbiota is well known to be linked with multiple immuno-oncological processes (*59–61*). Presented effects could be exploited in the future for the development of novel anti-cancer drugs and treatments based on MgB_2.

MgB_2 nanosheets have also proved to have a good osteogenic potential for bone disease-related therapeutics since they are able to enhance the osteoblast differentiation of mouse mesenchymal stem cells when embedded in polymeric scaffolds (*62*). Recent results based on *in vivo* experiments on mice suggest the use of bulk MgB_2 or of 3D printable polymer-MgB_2 in biodegradable bone implants (*63*, *64*). In both cases, complex shapes can be obtained opening the road for custom-oriented products.

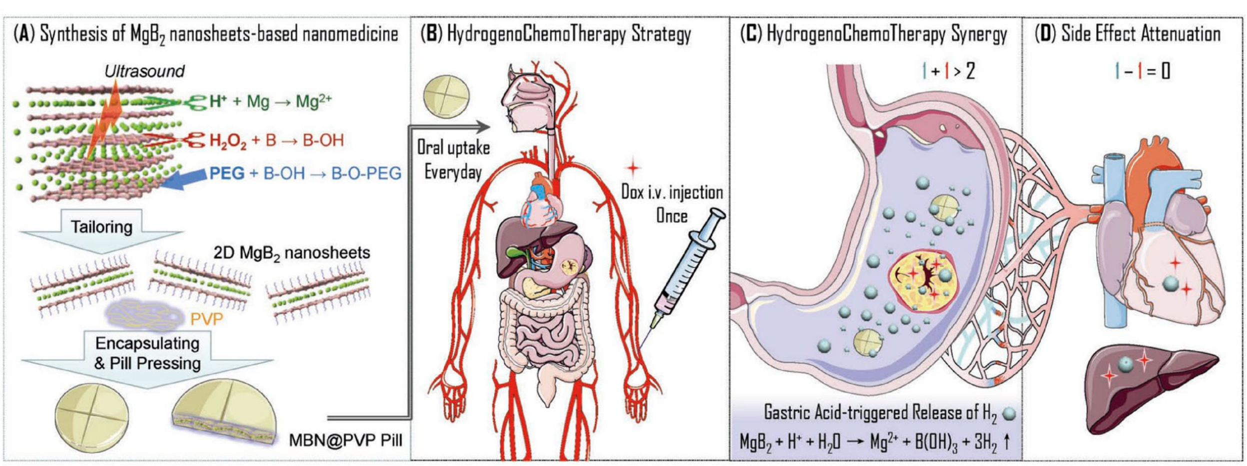

Figure 7. (A) Schematic illustration of the synthesis route of nano-MgB_2-PVP pills, (B) treatment strategy and (C, D) synergy/attenuation mechanisms of combined hydrogenochemotherapy (from ref. (*58*)).

MgB_2 is a valuable antimicrobial material being effective against Gram positive and negative strains. The growth of different bacteria and fungi was strongly inhibited, depending on the microbe. It is remarkable that the effect against microbes in planktonic state and against biofilms is comparable and it was observed at short (6 h) and long (24 h) incubation times. Therefore, MgB_2 inhibited both the initial phases of biofilm development and the mature biofilms. The *in vitro* results of excellent activity of MgB_2 on standard microbial lines were confirmed on 29 methicillin resistant clinical S. aureus isolates and 33 vancomycin resistant E. faecium/faecalis strains (*28*). The adherent microbial cells are known to be 100–10,000 times more resilient than individual microbes (*65*). The consequences are that biofilms pose a significant threat to human health and are responsible for 80% of human microbial infections (*66*). To combat them, high antibiotic doses are required, but excessive use of antibiotics and high adaptability of microbes promote the strengthening of the microbes' antibiotic-resistant behavior. Due to infections with antibiotic-resistant bacteria, only in the EU, 25,000 people die every year (*67*). Twenty new types of antibiotics were developed between 1930 and 1962, while from 1962 to the present, only two new types of antibiotics have gone into production (*68–70*). The slowdown in the development and commercialization of novel antibiotics and the problem of antibiotic-resistant microbes and biofilms need urgent measures and solutions. Nanomaterials, including MgB_2 are promising antimicrobial candidates, but much more research and technological developments are needed. For example, only one study on the *in vivo* antimicrobial activity of MgB_2 powder is currently available (*28*). It shows that MgB_2 treatment of infected mice led to a significant decrease of E. coli colonization in liver, spleen, and peritoneal liquid (Figure 8). The effective antimicrobial activity, tested *in vitro*, was measured on MgB_2 powders, as well as on biodegradable coatings of polyvinyl pyrrolidone (PVP) with embedded MgB_2 particles applied on different parts of a urinary commercial catheter (*56*) and on an orthosis (*71*), and on machinable by chipping MgB_2-hBN high density spark plasma sintered bulks (*72*).

The MgB_2 powders produced by infiltration of a reactive liquid (RLI) perform better than commercial powders (*73*), but the understanding of the reasons needs further effort and studies. In general, the details of the mechanisms and consequences of the MgB_2 – cells interactions are lacking or are insufficient, their research being in an early stage. This makes difficult analysis of some surprising experimental results with excellent practical and impact value. It is noteworthy to mention in this regard the following one. Addition of MgB_2 into commercial mouthwash with chlorhexidine ($C_{22}H_{30}Cl_2N_{10}$) produces an enhancement in its efficiency because of the antimicrobial synergetic effect against oral bacteria colonization and biofilms formation (*74*). The Global Burden of Disease Study (*75*), estimated that in 2017 oral disorders affected 3.47 billion people worldwide. Presented result can have significant positive consequences in stomatology, and it deserves further attention.

Use of MgB_2 in the biomedical field promises many interesting novel applications. According to results addressed in the previous paragraphs, internal and external use of MgB_2 seems possible. Medical devices such as prosthetics and biodegradable implants, drug delivery systems, self-sterilizing medical instruments, and many other kinds of medical items with time- and space-controlled activity can benefit from the application of MgB_2–based materials. We have also seen that MgB_2 is a candidate for development of drugs and solutions fighting

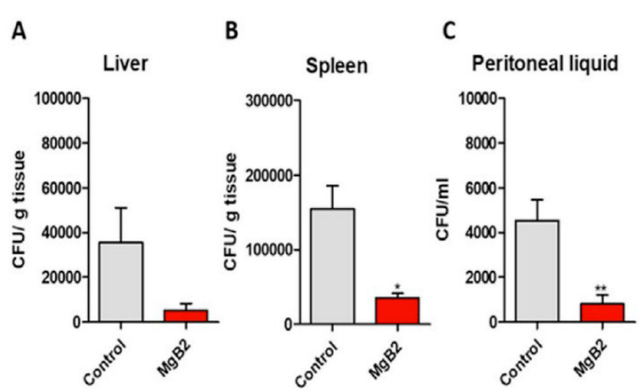

Figure 8. The average abundance (CFU/g) of E. coli in the liver (A), spleen (B), and peritoneal fluid (C) in nude CD-1 mice infected with E. coli and treated with MgB_2: $n = 4$, means ± standard error of the mean, unpaired t-test, in A – $p = .12$, B – $p < .01$, and C – $p < .05$ (from ref. (*28*)).

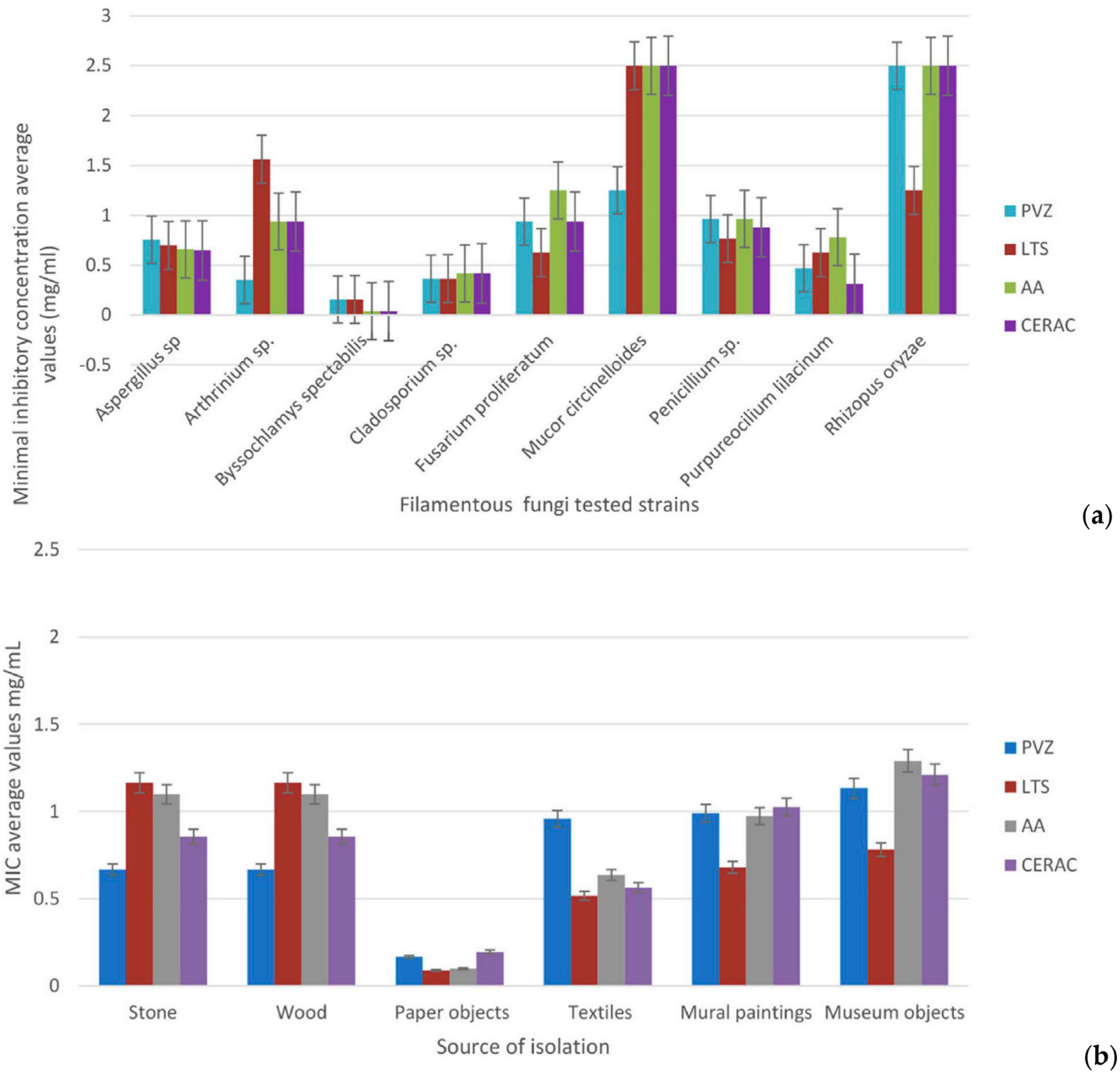

Figure 9. Minimal inhibitory concentrations (MIC) average values for different fungal strains belonging to (a) different genera or (b) when collected from different heritage objects. Four commercial MgB_2 powders denoted PVZ, LTS, AA, CERAC were used in the *in vitro* antifungal tests being supplied by Pavezyum Advanced Chemicals, LTS Research Laboratories Inc, Alfa Aesar, and CERAC Inc (part of Materion – Advanced Materials Group), respectively (from ref. (*57*)).

against cancer and infections. Given the anti-inflammatory effects of magnesium, one may also expect that the use of MgB_2 in antimicrobial formulations can lead to the alleviation of tissue damage caused by a vigorous inflammatory response when pathogens are present (*76*).

8. MgB_2 as an antifungal material for heritage and eco applications

The MgB_2 powders have been shown to be effective also against planktonic and biofilm fungi cells involved in the bio-deterioration of heritage buildings and objects (*57*). Minimal inhibitory concentrations average values for different fungal strains belonging to different genera or when collected from different heritage objects such as stone, wood, paper, textiles, mural paintings, and museum objects are presented in Figure 9. The values of <2.5 mg/ml are relatively low. At the same time the ecotoxicity results have indicated that tested MgB_2 powders can be considered ecofriendly at concentrations up to 20 mg/ml. In addition, it is noteworthy that water degradation of MgB_2 prevents its accumulation in the natural environment. This article opens a new practical field of applications of MgB_2, shifting from the superconductivity, energy, and biomedical fields to other different domains. Based on biodegradation and biocompatibility, the antimicrobial effect of MgB_2 can be of interest in the heritage conservation and restoration. We also mention water management of potable water, biofouling applications, packaging in the food industry, cleaning, and so on.

9. Concluding remarks

Our analysis suggests that MgB_2 has a promising future as a versatile material useful for many applications, superconducting or beyond, showing high potential of being well integrated with bio, health, ecology, and environmental top demands of the present and future clean economy. It is anticipated that MgB_2 can have a major impact on various industries and on life quality. It is a valuable example to illustrate and propose a path, direction, or solution as a possible viable answer to one of the most difficult and complex questions concerning materials future research and use: *Quo vadis materia*? From a practical viewpoint, materials close to the nature cycles are of key importance and investigation of their complex bio-eco-physical–chemical properties can be rewarding. The presented case study based on the MgB_2 multi-functionality, reviewed in this work, indicates that criteria by which materials are selected for an application need careful re-evaluation and refinement.

Author contributions

Authors equally contributed to conceptualization, methodology, and analysis. P.B. wrote the original draft and D.B. involved in review and editing.

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