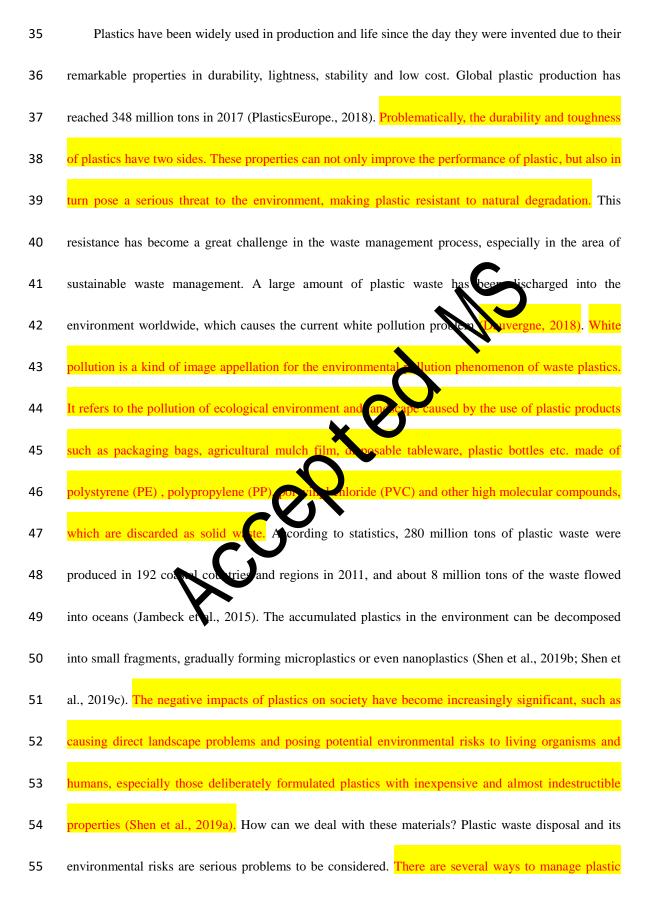
| 1 | Are biodegradable plastics a promising solution to solve the global plastic pollution? |
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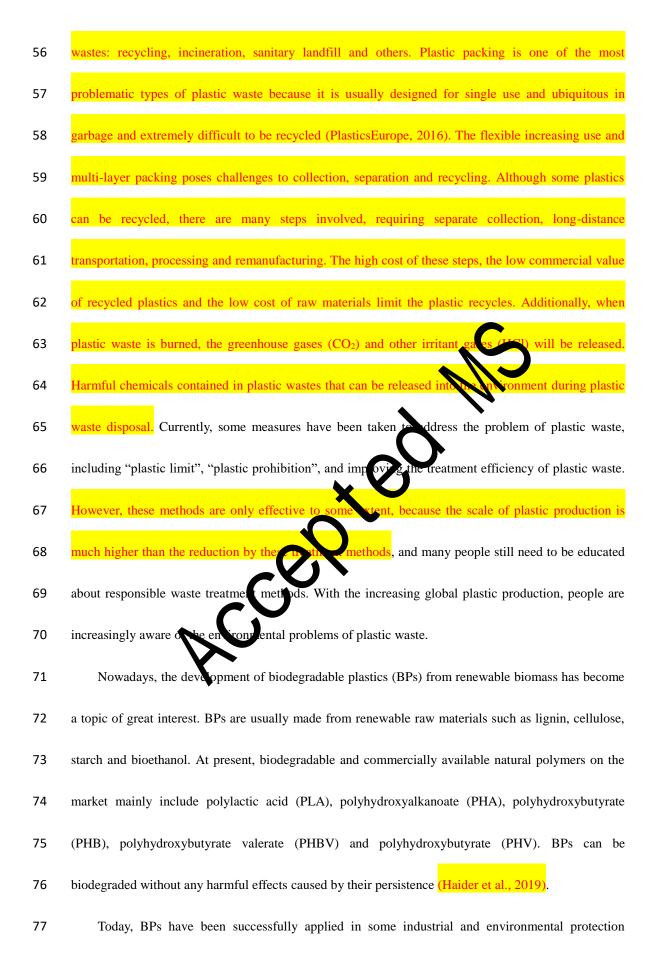
13 A large amount of plastic waste has been discharged into the environment worldwide, which 14 causes the current white pollution problem. The accumulated waste plastics in the environment can be 15 furtherly degraded into small pieces such microplastics and nanoplastics through weathering, which 16 will do more harm to the environment and humans than large plastics. Therefore, plastic production 17 and disposal are needed to be considered. Biodegradable plastics (BPs) have become the focus of 18 recent research due to their potential biodegradability and harmlessness, which would be the most 19 effective approach to manage the issue of plastic waste environmental acc mi n. However, in the long run, it is uncertain whether BPs can be a promising solution to 20 osal and global plastic 21 pollution. Consequently, both sides of the dispute are dis ed in this paper. At present, most 22 conventional plastics can not be replaced by these nodegradation of BPs needs certain B environmental conditions, which are not always reliable in the environment. Additionally, changes in 23 evelopment and application of BPs. BPs should not 24 human behavioral awareness will also 25 be considered as a technical solu on, this excusing our environmental responsibility, because littering of an effective technology. As such, the conclusion is that BPs may 26 does not change with 27 be a part of the solution. The effectiveness in providing environmentally solutions for plastic waste 28 management depends on the combination of affordable waste classification technologies and 29 investment in organic waste treatment facilities. Therefore, there is still a long way to go to solve the 30 global plastic pollution through BPs.

31 Keywords: Biodegradable plastic; Global plastic pollution; Plastic waste disposal; Biodegradation;
32 Potential solution

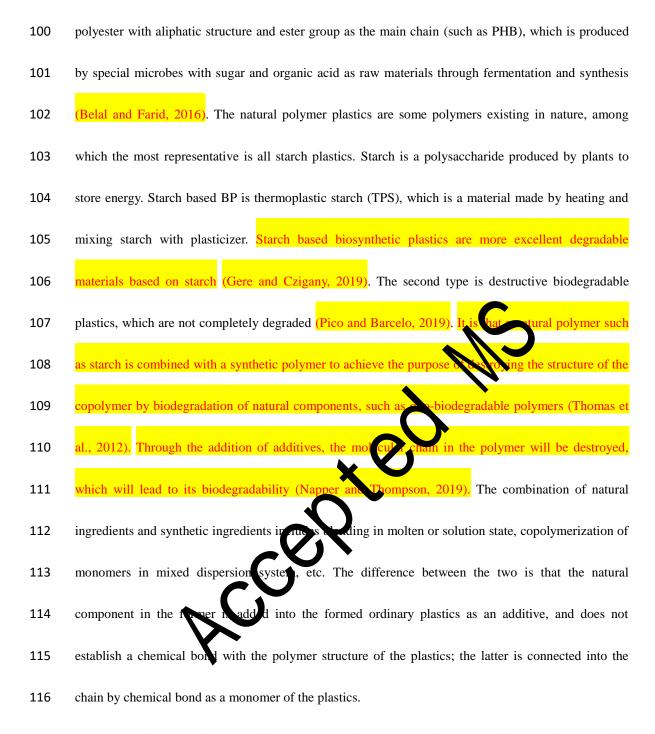
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34 1. Introduction





78 programs. Although some BPs have shown excellent physicochemical, mechanical and degradable 79 properties in many industrial applications, it is well known that BPs are currently not a substitute for 80 conventional plastics (Rujnićsokele and Pilipović, 2017). In the view growth of BPs, there is an impact 81 of knowledge gap to seek attention in this area. Consequently, there is still a question whether BPs can 82 be a promising solution to solve the waste disposal problem and global plastic pollution in the long run. 83 Herein, the both sides of the dispute about BPs are discussed in this paper. The application of BPs and 84 the challenge of solving environmental plastic pollution, and some perspectives are also raised. 85 2. What are BPs? Degradable plastic refers to a kind of plastic whose properties ca 86 use requirements and remain unchanged during the storage period, but can be degra 87 to environmentally sound substances 88 under natural environment conditions after use. BPs ar e of plastics that can be biodegraded 89 and disappeared in the natural environment (Pico and Rarcelo, 2019). Its degradation principle is that it 90 algae, etc.) existing in the nature to materials (CO_2 , can be decomposed by microbes (bac 91 n be negrated into the natural ecosystem without ecotoxic effect or H_2O , CH_4 and biomass), which d 92 residual by-products is a kind of polymer material, which has excellent performance and 93 can be slowly biodegraded, and finally it exists in nature as a part of carbon cycle. According to the 94 degree and nature of biodegradation, BPs can be divided into two types: completely biodegradable 95 plastics and destructive biodegradable plastics. The first type is fully degradable, which is made of 96 natural polymers such as starch, cellulose and chitin or agricultural and sideline products through microbial fermentation or synthesis into degradable polymers (Iannotti et al., 2018). According to the 97 98 source of new materials, BPs can be roughly divided into three categories: microbial synthetic plastics, 99 natural polymer plastics and synthetic biodegradable plastics. Microbial synthetic plastics are a kind of



Due to its good biodegradability, BPs are mainly used as soft and hard food packing materials. Packing is the largest application filed of BPs at present (European Bioplastics, 2019). The best-selling products are garbage bags, soft packaging, rigid packaging and disposable ceramics. In the future, the main market of BPs is plastic packing film, agricultural film, disposable plastic bag and disposable plastic tableware. Compared with conventional oil-based plastic materials, the cost of BPs is slightly

higher (Rujnićsokele and Pilipović, 2017), but people are willing to choose new BPs with higher price
to protect the ecological environment. Therefore, the BP industry has a huge development prospect and

124 broad application market.

125 3. Can BPs solve the problem of plastic environmental accumulation?

- 126 With the rapid development of petrochemical industry, plastics have gradually penetrated into 127 every aspect of daily life, followed by the problem of "white pollution" which can not be ignored. 128 These most incorruptible waste plastics not only do harm to human health, but also to the ecological 129 environment (Shen et al., 2019c; Shen et al., 2019d). At present, the com tment methods for waste plastics are incineration, landfill and recycling. 130 and landfill are the 131 the environment such as release of great pollu most negative treatment methods 132 stimulate gas and leakage of leachate, and are ver Recycling is another relatively good 133 way, however, actually, only a small percentage of ecyclable" plastic wastes are recycled into the d plastics (Ellen MacArthur Foundation, 2016). original products, even the most 134 135 Challenges lie in the use of colo ants, additives and fillers in the plastic production process, pollution 136 production during recycling. ow-grade plastic waste, such from consumer use multi-layer plastic packi 137 and plastic film, is particularly difficult to separate and dispose. The plastic 138 an only be recycled about 2-3 times before its quality drops to the point where it can no longer be used 139 Sedaghat, 2018). Each cycle of the recycling process shortens the length of the polymer chain, thus 140 causing mass loss and requiring further material treatment. As such, the best way to deal with waste 141 plastics is to make them decompose into harmless CO₂ and H₂O in natural state to return to nature. 142 Plastic is a kind of high molecular compound which is polymerized by monomers. The long chain
- 143 of carbon molecule in its structure is very firm and not easy to break, which is the main reason why

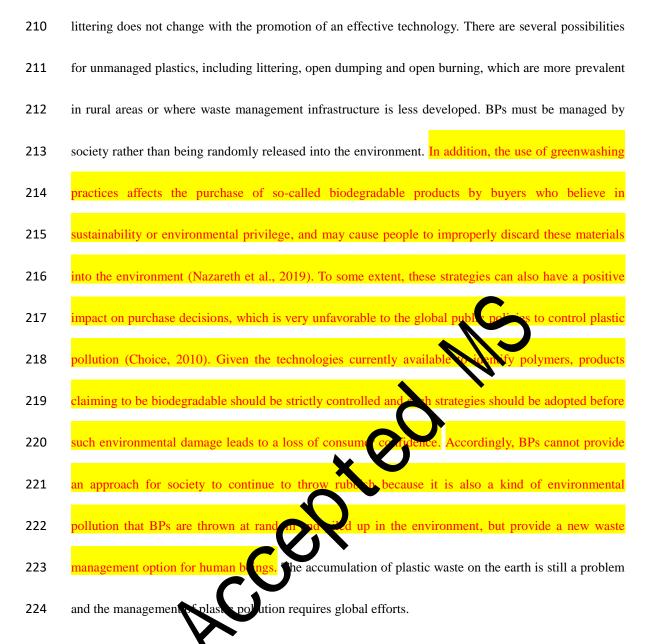
144 conventional oil-based plastics are difficult to decompose. The principle of BPs is to reduce the 145 difficulty of breaking the long chain of carbon molecule, so that it is easy to decompose from polymer 146 into small pieces, and then further degrade into CO₂, H₂O, and biomass. Unfortunately, however, there 147 are still questions whether BPs can be a promising solution to solve the waste disposal problem and 148 global plastic pollution. Accordingly, three scientific evidences are discussed here. 149 Firstly, it is well known that BPs are currently not a substitute for most conventional plastics. At 150 present, only PP and PE are the most common petroleum based plastics in the world (Geyer et al., 151 2017). Global plastic production has reached 335 million tons in 2016 and n tons in 2017 and is growing (PlasticsEurope., 2018). BPs only accounted for 0.5% of 152 5 million tons of the annual plastic production, and are expected to increase to ab 2.62 million tons in 2023 (European 153 Bioplastics, 2019). Although the production of BPs is 154 asing, it is no more than a drop in the 155 bucker to solve the global problem of plastic envir nmental accumulation. The key reason is cost. Plastic is too cheap, the production o mature, and the use is too large in the world. 156 157 According to the analysis, the pr e of \mathbf{P} produced by the current process is about several times (3 – nd PE (Luvt and Malik, 2019). Moreover, some BPs are not as good 158 10 times) that of conv PP. ior 159 as conventional plastics Shahlari and Lee, 2012). For example, PHB has better barrier properties than 160 which makes PHB superior to commercial plastics in the packaging of oxygen-sensitive products 161 such as food and beverages. However, its application is still limited due to its low plasticity and impact 162 strength, which results in many difficulties in polymer processing. The above two factors greatly limit 163 the popularization and application of BPs and hinder the substitution of BPs for petroleum based 164 plastics.

165 Secondly, the production of BPs seems to be much easier than their treatment. Degrading a

166 polymer, especially conventional plastics, requires more energy and exertions, which may also occur 167 on BPs. Biodegradability is related to the chemical properties of polymers and the environmental 168 conditions. Biodegradation is the processing of using living organisms (bacteria, fungi, etc.) to degrade 169 BPs into oligomers, monomers or CO_2 and H_2O , and eventually entering the ecosphere. The 170 biodegradation mechanism of BPs is illustrated in Fig.1. Biodegradation usually involves three phases: 171 biodeterioration, biofragmentation, and bioassimilation (Emadian et al., 2017). BPs have long chain, 172 high molecular weight and complex chemical structure, which means that they can neither be ingested 173 by microorganisms nor further degraded via cell membranes. In biodete living organisms 174 aggregate on the surface or inside of environmental BPs to form biofil bial colonization), and 175 the properties of BPs would be changed due to the nuous growth and reproduction of 176 microorganisms. In biofragmentation, BPs are graduall a into oligomers and monomers in the presence of depolymerase produced by microorganicas. Finally, these substances are assimilated by 177 arces and then converted into CO₂, H₂O and other microorganisms to provide carbon an 178 s are released back into the environment, the whole biodegradation 179 materials. When these metabolit 180 process of BPs is co ver, biodegradation of BPs needs certain environmental conditions, 181 which is controlled by oxygen content, ambient temperature, pH, water content, polymer characteristics, 182 etc. (Fig.1). A fact is that BPs can be biodegraded but the degradation process needs specific conditions that are not always reliable under the natural conditions (Nazareth et al., 2019). For example, the slow 183 184 degradation of BPs in marine environment has been noted (Morohoshi et al., 2018; Sashiwa et al., 2018), and the non-degradability of BPs has also been observed ins some cases (Napper and Thompson, 185 186 2019). Consequently, these factors in the biodegradation process must be considered. The time of 187 biodegradation controlled by polymer characteristics is critical for determining the applicability of BPs

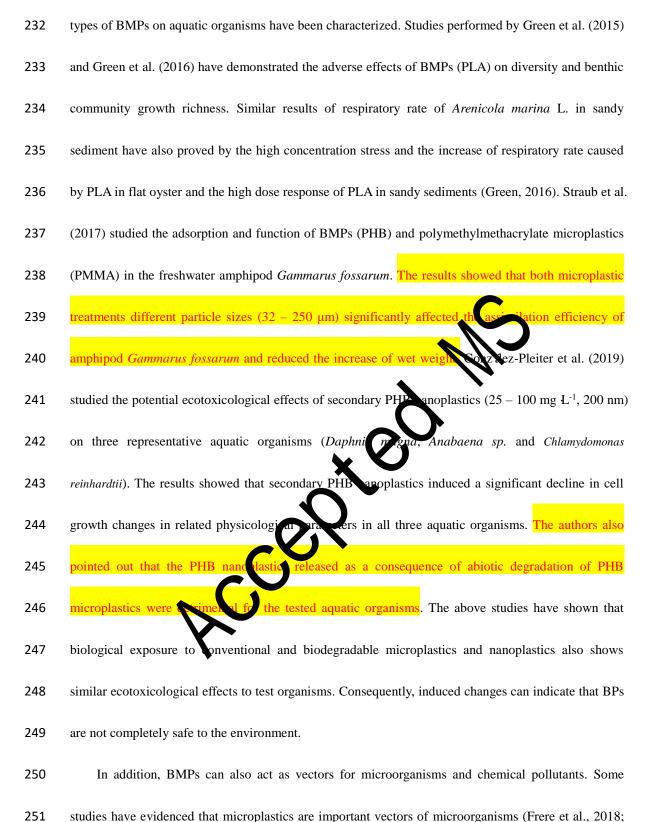
188 to end-of-life management technologies or their possible fate in the environment. If the biodegradation rate is not significantly different from that of conventional plastics of the same kind even in the 189 190 presence of microorganisms and key enzymes, limited biodegradability ill not benefit the environment 191 or the management of BP wastes. Biodegradation depends on the complexity, the chemical structure 192 and the crystallinity of the polymers. BPs with functional groups (-COO-, -OH, and -COOH) and 193 with flexible active sites have higher degradation rates because these active groups can bind to enzyme 194 sites much faster than those on rigid BPs. Shorter polymer chains lead to faster degradation, and 195 complex chemical structures (e.g., PHB) require additional enzymes or con nzymes (Narancic and O'Connor, 2019). Ambient temperature and pH will affect the bio 196 n rate because surface cracking of BPs caused by temperature and pH changes will. 197 elerate the degradation. The presence of plastic additives in BPs may also interfere with the b 198 tation process. Additionally, large-scale od⊧ disposal of BPs must be also considered. The production and consumption of large quantities of BPs 199 mean that a promising solution for lar 200 ment is needed. Large-scale plastic waste is usually 201 disposed of by landfill, incinera on, bological treatment (composting and anaerobic digestion), and posting is the main concern in the management of end-of-life of 202 recycling. Currently, BPs (Narancic and O'Onnor, 2019). Before composting, BPs suitable for composting should be 203 204 collected and separated through separate collection schemes and transported to industrial composting 205 facilities.

Thirdly, change of human behavioral awareness is important. The solution to the problem of global plastic pollution needs a change in human behavioral awareness combined with viable promising approaches, and the latter will be largely ineffective without the former. We should not consider BPs as a technical solution, thereby excusing our environmental responsibility, because



4. What are the potential risks of using BPs to the environment?

BP is also a kind of plastic, which inevitably has a potential impact on the environment during its application. When BPs are disposed in an uncontrolled manner, there are two fates in the environment: accumulate and break up. Like conventional plastics (PE and PP), BPs can also fragment into microplastics and nanoplastics. Recently, scientists have begun to study the impacts of biodegradable microplastics (BMPs) with the gradual understanding of BPs. Shruti and Kutralam-Muniasamy (2019) thoroughly discussed the potential effects of BMPs on the environment. The potential effects of limited



- studies have evidenced that microplastics are important vectors of microorganisms (Frere et al., 2018;
- 252 Shen et al., 2019d) and chemical pollutants (Hartmann et al., 2017; Koelmans et al., 2016; Pittura et al.,
- 253 2018; Ziccardi et al., 2016). Due to the similar characteristics of particle size, good fluidity and good

stability, BMPs also have a strong adsorption and enrichment tread for chemical pollutants and microorganisms. Recently, Zuo et al. (2019) investigated the adsorption and desorption of poly(butylene adipate co-terephtalate) (PBAT, $2338 \pm 486 \mu$ m), PS (250 µm) and PE (2628 ± 623 µm) for traditional organic pollutants (phenanthrene). The results showed that the adsorption and desorption capacity of PBAT BMPs was significantly higher than that of PS and PE microplastics. The authors further reported that BMPs were a strong vector of phenanthrene compared with the conventional microplastics.

Unfortunately, however, it is too early to assert the threat state (with 261 t threat) of BMPs due to the lack of data in this respect. Few studies have found the 262 BMPs on very limited aquatic organisms. The potential effects of BMPs have not 263 performed in many cases, and it is 264 unclear for a series of animals used as human food. it is difficult to determine the more of organisms, ecosystems and humans. The 265 specific threat that BMPs may pose to the hear 266 coecological effect of BMPs on ecos be a concern issue in the future. It is necessary to 267 evaluate and integrate the effect on human food safety and health by testing the potential effects of 268 BMPs on different of cosystems.

269 5. What is the function **f** BPs in solving plastic pollution?

Although the current level of substitution is very low, BPs can replace most of the conventional plastics currently in use and consumption. Shen et al. (2009) investigated the potential technology substitution of BPs for conventional oil based plastics. The authors reported that the largest substitution rate could reach up 94%, of which 31% were BPs and 63% were biobased plastics but not biodegradable plastics. However, the actual level of production and substitution is still far from the theoretical maximum. Because of economic factors, difficulties in rapid scale and the availability of BP

- raw materials, and slow adoption of new BPs in the plastic industry, this potential may not be exploited
- in the short and medium term. Although BPs are still in the development stage, and the market is not
- fully formed as a whole, it has shown the substitution effect on conventional plastics in some fields.
- a) Disposable plastic products
- 280 There are a large number of disposable plastic products in daily life, such as plastic bags, garbage 281 bags, disposal plastic lunch boxes and tableware, product packing bags. This kind of these products is 282 widely distributed in our daily life, with a large amount of consumption, but as the same time, they produce a series of problems such as white pollution. For BPs, disposable 283 ducts are the most 284 potential application areas in the future strategy of realizing low nomy and sustainable development of industry. BPs used for disposable products neg 285 have a faster degradation speed, and 286 their mechanical properties should be able to meet the s quirements of daily use.

b) Agricultural application (biodegradable plastic mulch film)

roduction is a kind of high molecular hydrocarbon At present, most of the mulch fi 288 f PP low molding. Conventional high polymer plastics have good 289 transparent film, which is made f years for the residual film to become harmless material to the soil. 290 strength, and it will The residual plastic film in the soil has a bad effect on the arable and aeration of the soil, and even 291 292 leads to the decreases of crop yield. The harm of plastic mulch film pollution is mainly manifested in 293 the following aspects: (1) reducing the level of soil fertility; (2) affecting the fertilizer efficiency; and 294 (3) making the crop malnutrition. The treatment of residual mulch film is mainly driven by 295 administrative forces, mechanical recovery and manual pickup. Unfortunately, however, no matter 296 mechanical or manual, the accumulation of residual mulch film cannot completely remove for a long 297 time, and the cost of recovery of residual mulch film is also gradually rising. The most feasible way to

- solve the problem of residual film is to use agricultural degradable mulch films. On the one hand, the
- degradable film has the same effect as the conventional film (PBAT vs PP), and at the same time solves
- the inevitable residual film pollution caused by the conventional film. On the other hand, large-scale
- 301 promotion of degradable mulch film can play a role in resolving traditional excess capacity.
- 302 c) High-end market
- 303 The application of BPs in high-end market includes medical supplies, drug release materials, 3D
- 304 printing materials, etc. PLA, PHA, polycaprolactone (PCL) and other BPs have good biocompatibility,
- 305 which can be controlled by molecular design synthesis, so they have development of the potential in high-end
- 306 market. PLA is one of the most commonly used 3D printing wires. Compared with other used 3D
- 307 printing materials such as acrylonitrile butadiene styrene, PL has many advantages: it not only has
- 308 rich colors and good transparency, but also can achieve righer printing speed and better printing;
- 309 moreover it is environmentally friendly. Because of road biocompatibility, PHAs are widely used in
- medical fields, such as medical suture rep in take, orthopedic needle, guided tissue repair, articular
 cartilage repair stent, etc. PCL as good thermoplasticity and molding processability, which can be
- made into fibers, flates shots, ec. Due to their special properties, BPs will play more irreplaceablerole in the high-end filed and have broad development spaces.
- **6.** What are the opportunities and challenges of using BPs?

BPs are of great significance for global environmental protection. The emergence of BPs is an inevitable requirement for the sustainable development of the environment in the 21st century. Therefore, it is common goal for all countries in the world to strengthen the research on BPs and promote the product development of BPs. The challenge comes from promoting this alternative potential. There are four important factors: technical aspects, financial, management and consumers 320 (Fig.2).

321 Firstly, the development of technology plays a big role in the acceptance rate of BPs. In the 322 existing technology, there are methods to improve the thermal stability and mechanical strength of BPs 323 by compounding with inorganic materials. It will also cause the increase of degradation products and 324 the decrease of degradation rate. The biodegradation performance of BPs is realized by degradation of 325 macromolecules into micromolecules by environmental microorganisms, and this degradation process 326 is very slow, especially the resin molecular materials. It is difficult to recycle the waste plastics, and 327 whether the degradation products will not pollute the environment remains died. Additionally, 328 large-scale disposal of BPs must be also considered. Improvements ompost infrastructure, including compost classification and BP recycle, will allog 329 or the treatment of BPs in compost 330 facilities (Andrade et al., 2016). Therefore, waste mana nu public behavioral awareness are the 331 important factors in solving the problem of plastic a sumulation in the environment, but they are not evelopment of new materials are also considered in 332 fundamental. The progress of technological 333 the future. 334 Secondly, finan greatly inhibit the development of BPs. Compared with conventional

plastics, the material price for producing BPs is relatively high, and the technical process is complex, so the final product price is far high than that of conventional plastics. Cost has always been an important indicator of whether a product can be applied to the market on a large scale. Therefore, the price of agricultural raw materials should be monitored to ensure that they are competitive with fossil fuels, so as to promote the transfer of conventional materials to biodegradable materials. Moreover, new equipment and synthesis process should be optimized to reduce the production cost of BPs. 342 materials, which is also an important measure to reduce costs.

343 Thirdly, the BP industry lacks a favorable management system. There are three ways to manage 344 plastic wastes: recycling, incineration, and sanitary landfill. Due to the chaotic collection system of 345 conventional plastic and BP, the disposal of plastic wastes has become difficult. BPs can be burned like 346 conventional plastic, and the energy of BPs is similar to that of conventional plastics (Dilkes-Hoffman 347 et al., 2019). However, in terms of landfill, conventional plastics and BPs are quite different. 348 Conventional plastics are difficult to decompose in landfill. During degradation of BPs in landfill, methane, a higher global warming potential gas than CO₂, can be produced Ind 349 ial composting and 350 anaerobic digestion are also concerns in the management of end-of-li However, before that, BPs suitable for composting and anaerobic digestion show 351 be collected and separated through 352 separate collection schemes and transported to industria ung and digestion facilities. 353 Finally, raising the environmental awareness of be public is also an essential part of promoting BPs. How to identify and deal with BI a major concern of the public, but also a problem to 354 355 be solved. It is recommended t develop identification codes for BPs (bags, containers, and other m other recyclable materials. This needs to be combined with local 356 materials) to help set 357 education on how iden ify and deal with BPs. BPs may not have an adverse impact on waste management if appropriate labelling and differentiated waste collection systems are developed. 358

359 7. Conclusion

The accumulation of plastics on the planet is a severe problem in this time. The severity of this problem will exponentially increase with the increase of global plastic production and consumption. As such, measures should be taken to reduce the rate of plastic accumulation and the ecological effects caused by the inevitable accumulation. BPs can effectively protect and improve the environment, and

364 greatly promote the development of environmental protection. However, the production of BPs seems 365 to be much easier than their treatment. The performances of BPs are greatly questioned. There is no 366 answer whether BPs can be a promising solution to solve the waste disposal problem and global plastic pollution. Many aspects of BPs are still in their infancy. There is no single solution to solve the 367 368 problem of plastic accumulation in the environment, it is important to determine the effective 369 combination of solutions. Just for now, BPs should be a part of the solution, albeit a very small part. The effect of BPs on plastic accumulation should not be underestimated. In addition, under the severe 370 situation of energy conservation and emission reduction, the developm 371 Ps is of strategic significance. Therefore, we still have a long way to go to solve the gl 372 pollution until (a) all 373 non-biodegradable plastic products can be replaced by BPs the same or similar performance; (b) everyone in the world can dispose of BP waste acc 374 egulations and laws and should be rdi 375 responsible for our environment; (c) the can be biodegraded on a large-scale, and the 376 ecosystem; and (d) raw materials for BPs can be biodegradation byproducts can be r tained from the environment. 377 continuously and inexpensively of 378 Acknowledgements 379 The study is financially supported by the Program for the National Natural Science Foundation of

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383 Declaration of interest

384 The authors have no conflict of interest to declare regarding this article.

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