



REVIEW

Knowledge and Opportunities from the Plastisphere: A Prelude for the Search of Plastic Degrading Bacteria on Coastal Environments

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ABSTRACT

Plastic pollution has become an urgent issue, since its invasion to every ecosystem has led to multiple impacts on the environment and human populations. Certain microbial strains and genera had shown the ability to biodegrade plastic sources under laboratory conditions. In this minireview, we collect and analyze scientific papers and reports of this microbial activity as we contextualize this information on the global plastic pollution problem, to provide an updated state of the art of plastic biodegradation with microbial agents. Along with a broad understanding of the general process of plastic biodegradation hosted by microorganisms. The contributions of this minireview come from the identification of research gaps, as well as proposals for new approaches. One of the main proposals focuses on coastal environments and in particular coastal wetlands as a great microbiome source with potential for plastic biodegradation, whether reported or undiscovered. Our final proposal consists of the application of this knowledge into technologic tools and strategies that have a remarkable impact on the battle against the plastic pollution problem.

1. Introduction

The plastic pollution problem

Plastics are synthetic or semi-synthetic polymers mainly produced from petrochemicals, characterized by their high resistance/density relationship, their great thermal and electric isolation properties, as well as resistance to acids, alkalis and solvents^[1]. These materials have applications in multiple industries and business sectors like trading, packing, building materials, medical and pharmaceutical uses, automotive industry, home appliances, agriculture and many mass production products for the every-

day human consumption^[2,3].

These polymers pollute and invade a lot of environments due to the single-use and improper waste management. The main plastic types considered environmental pollutants are High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polyvinyl Chloride (PVC), Polystyrene (PS), Polypropylene (PP), Polyester (PES), Polyamide (PA) and Polyethylene terephthalate (PET)^[4].

Plastic pollution has become one of the biggest environmental threats by invading every ecosystem. It has been reported the presence of plastic debris (microplastics)

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from deep-sea sediments^[5], to the highest areas of the mount Everest^[6]. The presence of microplastics in the human placenta has been documented as well^[7].

Around 13 million tons of plastic have been thrown to oceans annually, besides the global annual production of 300 million tons of plastic debris^[8]. In México, nearly 83,343 tons of trash are collected daily^[9] and in the municipal solid waste composition, plastic spans 10.9%^[10].

Main consequences of this pollutant relay on contamination of water sources like rivers, lakes or oceans leading to the formation of continental sized trash patches in the middle of the Pacific Ocean^[11]. Also, additives and other compounds present in plastics impact on coastal, marine and inland soils, damaging their physicochemical properties and fertility^[12].

Biotic impacts come from mutilation, intoxication and asphyxia of marine, coastal and terrestrial organisms^[13]. Human population affectations include the intake of microplastic polluted food^[14] to neurotoxic damage from PAH's, Phthalates and PCB's^[15]. Furthermore, plastic residues represent public health and economic hazards to human communities.

2. Coastal Wetland Ecosystem Goods and Services

Worldwide ecosystems shelter goods and services that provide human populations resources for their basic needs; these so-called ecosystem services and natural capital^[16] are in decay because of environmental issues such as plastic contamination. This situation is a threat to global human economics and welfare, ever since biodiversity is linked in so many complex ways to ecosystem functionalities and their output ecosystem services^[17].

Particularly, coastal wetlands provide human population wide and diverse goods and services due to the enormous biodiversity within these ecosystems. Some of these goods and services are categorized as ecosystem services framework^[18]. Supporting ecosystem services include the primary production of microbiotic (bacteria, fungi, protozoa) and macrobiotic (migratory birds and commercial interest fish and crustaceans) life forms, soil formation and enrichment. Provisioning goods and services are represented by sources like fresh water, seafood, honey and woods. Regulating functions such as climate regulation by carbon dioxide sequestration and flood and storms mitigation. The Cultural category is covered as aesthetics, recreational, educative and spiritual values for native human population as well as foreign people through ecotourism^[19].

3. Microbial Biodegradation of Plastics

Environmental plastic pollution solutions have become an urgent subject and an interesting approach could be just below ourselves. Diverse microbes have shown the ability to degrade plastics; particularly bacterial strains isolated from different environments that have been studied and reported in diverse scientific publications. Some of these papers are reviewed in the present study.

Bacteria have been widely researched in plastic biodegradation matter, since they are easy for cultivation and isolation, and the facility for bioprospecting metabolic pathways, ecological functions and subproduct related information through metagenomic analysis and sequencing of the 16S ribosomal gene^[20,21]. In this review, scientific evidence of plastic biodegradation hosted by bacteria dates from at least 1991^[22,23]. In general, research has focused on confirming and assessing plastic degradation by bacteria either through in vitro or in situ assays.

Depolymerization activity is usually measured with diverse methodology such as visual assessment through detecting roughening, cracking and biofilm formation^[24], clear-zone tests^[25], weight loss estimates in microbial exposure^[26], respiratory activity evaluation such as CO₂ production or O₂ consumption^[27]. As well as detection of the activity of specific enzymes or byproducts of depolymerization activity^[28,29].

4. Bacterial Biodegradation State of the Art

In the present review, we summarize some bacterial strains and species that have the ability to biodegrade plastic, with complementary information about the habitat of the bacteria, type of plastic degraded, byproducts, enzyme and the bibliographic reference to the paper. This information is categorized and divided based on the type of environment where the bacteria were isolated.

Table 1 shows previous scientific research results from bacteria isolated from anthropic environments, such as municipal waste disposal sites, sewage water, industrial activated sludges or purchased pre-cultured strains from laboratories and microbial strains collections.

Aquatic environment native bacteria are represented in Table 2. Aquatic environments that hold bacterial sources are wide and diverse and some of the most studied environments are sea water and soil, abyssal water and soil, freshwater like rivers and lakes. Some of the least studied are coastal soil and water, highlighting coastal wetland ecosystems.

Table 1. Municipal waste disposal sites/Other Human environments

ID	Habitat	Plastic type degraded	Degradation by-products	Enzyme	Reference
<i>Pseudomonas, Penicillium, Rhodotorula, Hyalodendron</i>	Landfill	Low Density Polyethylene (LDPE), Polyurethane (PU), Polyvinyl chloride (PVC) Polyethylene glycol	—	Alcano monooxygenase, same as found on hydrocarbon biodegradation (Seneviratne, 2006)	[26]
<i>Ideonella sakaiensis</i>	Sediment from PET-recycling site.	Polyethylene terephthalate (PET)	Terephthalic acid (TPA) & ethylene glycol (EG)	Mono(2-hydroxyethyl) (MHET) terephthalic acid	[30]
<i>Pseudomonas</i>	Final waste deposition site	Low Density Polyethylene (LDPE)	—	—	[31]
<i>Pseudomonas MYK1 and Bacillus MYK2</i>	Digester sewage sludge	Polylactic Acid (PLA)	CO ₂ and CH ₄	—	[27]
<i>Comamonas acidovorans</i>	City soil samples	Polyester-type polyurethanes	Adipic acid and diethylene glycol	—	[32]
<i>Pseudomonas aeruginosa</i>	Previously isolated microorganisms (Microteca/microlibrary)	PET, PU, PP, ABS, HDPE, PVC, ABS, PS	—	—	[24]
<i>Acidovorax delafieldii</i>	City soil samples	Poly(tetramethylene succinate)-co-(tetramethylene adipate) (PBSA)	—	Lipase	[33]
<i>Bacillus subtilis, Bacillus cereus, Bacillus lentus, Pseudomonas aeruginosa, Staphylococcus aureus, Klebsiella pneumoniae, Streptococcus pyogenes, Escherichia coli, Proteus vulgaris, Micrococcus.</i>	FADAMA soil	Polythene plastic bags and environmental plastic materials	—	Polyurethanases (Koutny et al., 2006).	[34]
<i>Brevibacillus borstelensis</i>	Soil from Polyethylene waste deposition site	Branched low-density polyethylene	—	—	[35]
<i>Rhodococcus ruber</i>	Sediments with polyethylene debris from agriculture use	Polyethylene	—	Esterases	[36]
<i>Streptomyces viridosporus, Streptomyces badius and Streptomyces setonii</i>	Enzymes from cultured <i>S. viridosporus, S badius and S setonii</i>	Starch-polyethylene degradable plastic films	Primary and secondary alcohols	—	[23]
<i>Pseudomonas putida</i> (AJ) and <i>Ochrobactrum</i> (TD)	Dangerous waste disposal site	Vinyl Chloride	—	—	[37]
<i>Pseudomonas fluorescens</i>	Naval Research Laboratory, Wahington D.C.	Polyester polyurethane	—	Enzyme with protease activity	[38]
<i>Thermomonospora fusca</i>	Compost from green waste	Aliphatic-Aromatic Copolyesters (synthesized from 1,4-butanediol, adipic acid, and terephthalic acid (BTA))	—	—	[39]
<i>Schlegelella thermodepolymerans and Pseudomonas indica</i> (K2)	Activated sludge	Poly(3-hydroxybutyrate-co-3-mercaptopropionate). [poly(3HB-co-3MP)]	3HB Oligomer linked as thioester	Poly(3-hydroxybutyrate)(3HB) depolymerase	[40]

ID	Habitat	Plastic type degraded	Degradation by-products	Enzyme	Reference
<i>Clostridium botulinum</i> and <i>Clostridium acetobutylicum</i>	Sewage sludge and methane sludge	Poly(b-hydroxybutyrate) (PHB), poly(b-hydroxybutyrate-co-11.6%-b-hydroxyvalerate) (PHBV) and the synthetic polyester poly(ϵ -caprolactone) (PCL)	—	PCL depolymerizing	[25]
<i>Bacillus amylolyticus</i> , <i>Bacillus firmus</i> , <i>Bacillus subtilis</i> , <i>Pseudomonas putida</i> , <i>Pseudomonas fluorescens</i>	Municipal solid waste from compost plant	Polyethylene bags	—	—	[41]
<i>Bacillus cereus</i> , <i>B. megaterium</i> , <i>B. subtilis</i> , <i>Brevibacillus borstelensis</i>	Culture fields	Polyethylene	Hydrocarbons (saturated and unsaturated) and alcohols of higher molecular weight	—	[42]
<i>Rhodococcus rhodoshrous</i>	Purchased isolates from American Type Culture Collection	High density polyethylene (HDPE), Low density polyethylene (LDPE) and Linear low-density polyethylene (LLDPE) films with balanced content of antioxidants and pro-oxidants (manganese+iron or manganese+iron+cobalt)	—	—	[43]
<i>Actinomadura</i> sp. S14, <i>Actinomadura</i> sp. TF1, <i>Streptomyces</i> sp. APL3 y <i>Laceyella</i> sp. TP4	Compost soil	Polyester biodegradable plastics; polylactic acid (PLA), polycaprolactone (PCL), poly-(butylene succinate) (PBS) & polybutylene succinate-co-adipate (PBSA)	—	S14, TF1 & TP4 produced PLA and PBSA depolymerase (50°C), APL3 (40°C). <i>Actinomadura</i> sp. S14 (PCL depolymerase) <i>Actinomadura</i> sp.TF1 (PLA depolymerase), <i>Streptomyces</i> sp. APL3 (PBS depolymerase), <i>Laceyella</i> sp.TP4 (PBSA depolymerase)	[44]
<i>Paenibacillus amylolyticus</i> TB-13 (<i>Bacillus amylolyticus</i>)	Sediment samples from multiple sites	Poly(lactic acid), poly(butylene succinate), poly(butylene succinate-co-adipate), poly(ϵ -caprolactone) and poly(ethylene succinate)	—	Proteases and esterases	[45]
<i>Streptomyces</i> sp. AF-111	Sewage sludge from Treatment Plant Rawalpindi Pakistan	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV)	—	PHBV Depolymerase	[28]
<i>Bacillus</i> sp. AF8, <i>Pseudomonas</i> sp AF9, <i>Micrococcus</i> sp. 10, <i>Arthrobacter</i> sp. AF11, and <i>Corynebacterium</i> sp. AF12	Soil from plastic deposition sites	Poly [4,4'-methylenebis (phenyl isocyanate)-alt-1,4-butanediol/poly (butylene adipate)] (Polyurethane, PU)	p-nitrophenol (Spectroscopy), CO ₂ (Sturm test)	Esterase Polyurethanases (plate assay with Coomassie blue R 250).	[29]
PN24 <i>Bacillus cereus</i> , PN12 <i>Bacillus pumilus</i> , LNR3 <i>Arthrobacter</i> .	Waste deposition sites and artificially developed soil beds containing maleic anhydride glucose, and small pieces of polyethylene.	High and low-density polyethylenes (HDPE/ LDPE)	—	—	[46]

Table 2. Marine, Freshwater and coastal environments

ID	Habitat	Plastic type degraded	Degradation by-products	Enzyme	Reference
<i>Pseudomonas</i> , <i>Staphylococcus</i> , <i>Moraxella</i> , <i>Micrococcus</i> , <i>Streptococcus</i>	Mangrove soil	Polyethylene bags and plastic cups	—	—	[47]
<i>Pseudomonas (Pseudomonas stutzeri)</i>	River water	High molecular weight Polyethylene Glycols (PEG's)	Glyoxylic acid	PEG dehydrogenase (Single polypeptide)	[22]
<i>Rhodobacteraceae</i> , <i>Rhodospirillaceae</i> , <i>Oceanospirillaceae</i> , <i>Glaciecola</i>	Seawater	Poly(3-hydroxybutyrate-co-3hydroxyhexanoate) (PHBH)	—	—	[48]
<i>Shenawella (CT01)</i> , <i>Moritella (CT12, JT01, JT04)</i> , <i>Psychrobacter (JT05)</i> and <i>Pseudomonas (JT08)</i>	Marine depths soil	Poly ϵ -caprolactone (PCL), aliphatic polyesters	—	—	[49]
<i>Terrabacter tumescens</i> , <i>Terracoccus luteus</i> , <i>Brevibacillus reuszeri</i> , <i>Agrobacterium tumefaciens</i> , <i>Burkholderia vietnamiensis</i> , <i>Duganella zoogloeoides</i> , <i>Pseudomonas lemoignei</i> , <i>Ralstonia eutropha</i> , <i>Ralstonia pickettii</i> , <i>Matsuebacter chitosanotabidus</i> , <i>Roseateles depolymerans</i> , <i>Rhodiferax fermentans</i> , <i>Variovorax paradoxus</i> , <i>Serratia marcescens</i> , <i>Acinetobacter calcoaceticus</i> , <i>Acinetobacter junii</i> , <i>Pseudomonas pavonaceae</i> , <i>Pseudomonas rhodesiae</i> , <i>Pseudomonas amygdali</i> , <i>Pseudomonas veronii</i>	Soil samples (ando-soil, woody area at Shima-Tsakuba, brown lowlands soils, sandy riverside soil and riverside mud)	Poly(β -hydroxyalkanoate), poly(ϵ -caprolactone), poly(hexamethylene carbonate), or poly(tetramethylene succinate)	—	—	[50]
<i>Bacillus mojavensis</i> TH309	Bio-deteriorated plastic waste from Tidal zone on Carsamba coast of Samsun	Poly(ϵ -caprolactone) (PCL)	—	Esterase (BmEST)	[51]
<i>Alcalinovorax</i> , <i>Hyphomonas</i> and <i>Cycloclasticus</i> .	Seawater and soil samples	Poly(ethylene terephthalate) (PET) & Biodegradable Plastic bags (BD)	Insoluble by-products of the hydrolytic degradation of PET.	Esterase	[52]
<i>Pseudomonas pachastrellae</i> JCM12285	Marine plastic debris in coastal seawater	Poly(ϵ -caprolactone) (PCL)	—	PCL hydrolase	[53]
Gammaproteobacteria, Alphaproteobacteria, and Flavobacteria (Class level)	Microplastics exposed to seawater from coastal zones	Polypropylene (PP) and polyvinyl chloride (PVC) microplastics	—	—	[54]
<i>Arcobacter</i> and <i>Colwellia</i>	Three types of coastal marine sediment from Spurn Point, Humber Estuary, U.K.	Low Density Polyethylene (LDPE) microplastics	—	—	[55]
<i>Bacillus cereus</i> and <i>Bacillus gothelii</i>	Sediments from Matang mangrove in Perak	Polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), and polystyrene (PS)	—	—	[56]
<i>Lysinibacillus fusiformis</i> strain VASB14/WL and <i>Bacillus cereus</i> strain VASB1/TS	Rhizosphere samples from mangrove (<i>Avicennia marina</i>) soil	Polythene	—	—	[57]

Microbial research has focused on new sources. One of the most popular in recent years is the gut microbiome from organisms such as Coleoptera, Lepidoptera, Lumbricidae and certain mollusks. Some organisms contain bacterial strains capable of degrading complex chemical structured materials such as wax or wood timbers. Assays on these organisms and their gut microbiota have shown a certain capacity of degrading plastic samples as well (Table 3). These host organisms could also be referred to as holobionts^[58].

5. General Process of Biodegradation by Microorganisms

For a better comprehension of the topic, a deeper understanding of the biodegradation process is required. Thus this metabolic mechanism is the core of the activity and eventual application of plastic degradation through

bacterial strains.

The biodegradation process may differ depending on the genera and species, but the main process is illustrated in Figure 1 and described as follows:

The general microbial biodegradation process can be described in three stages: Biodeterioration, biofragmentation and assimilation^[66]. At the time environmental abiotic degradation occurs via Mechanical, Chemical, Photocatalytic Thermal and Ozone-induced degradation^[67].

Biodeterioration

It all begins when the plastic material is exposed to the environment (where abiotic degradation factors join the process), then, bacteria start to settle down into the plastic surface to form a biofilm or the so called “Plastisphere”^[68]. Microbial activity of consortia (i.e. protein and enzymatic activity) causes deterioration of physical, mechanical and chemical properties of the polymer, leading to cracking of surfaces, formation of oligomers, monomers, as well as

Table 3. Macrofauna gut microbiome (Holobionts)

ID	Habitat	Plastic type degraded	Degradation by-products	Enzyme	Reference
<i>Escherichia, Shigella, Asaia</i> and <i>Acinetobacter; Rhodocytaphaga, Bergeyella, Diaphorobacter, Hydrogenophaga, Zhizhongheella.</i>	Gut microbiome from <i>Galleria mellonella</i>	Low-density polyethylene (LDPE)	Glycol	—	[59]
Enterobacteriaceae, Spiroplasmataceae, and Enterococcaceae	Gut microbes from <i>T. obscurus</i> and <i>T. molitor</i> (purchased from insect breeding plants)	Polystyrene (PS)	—	—	[60]
<i>Dyella, Lysobacter,</i> and <i>Leptothrix</i>	Microbes from larvae <i>T. molitor</i> gut. larvae purchased from market	Polystyrene (PS) and Low-density polyethylene (LDPE) Foams	—	—	[61]
Family Enterobacteriaceae, Sphingobacteriaceae, and Aeromonadaceae	Microbiome gut from Soil Snail <i>A. fulica</i> purchased from Jiaxing Hong-Fu Breeding farm (Zhejiang, China),	Expanded polystyrene (PS) foam	—	—	[62]
<i>Serratia sp.</i> strain WSW	Microflora from <i>P. davidis</i> larvae gut	Polystyrene (PS) Styrofoam	—	—	[63]
Actinobacteria (<i>Microbacterium awajiense, Rhodococcus jostii, Mycobacterium vanbaalenii</i> and <i>Streptomyces fulvissimus</i>) and Firmicutes (<i>Bacillus simplex</i> and <i>Bacillus sp.</i>)	Earthworm's gut	LDPE	Volatile compounds (octadecane, eicosane, docosane and tricosane) and nanoplastics	—	[64]
<i>Bacillus</i> and <i>Serratia</i>	Microbial gut from <i>G. mellonella L.</i> larvae purchased from Huiyude Co.	Polyethylene (PE) and polystyrene (PS)	Long chain fatty acids as the metabolic intermediates of plastics in the residual polymers	—	[65]

carbon and nitrogen sources [66].

Biofragmentation

In order to reach polymer assimilation, microorganisms have to break polymer bonds for cellular absorption of oligomers and monomers, since polymer chemical structure is too big and complex to be directly absorbed by microorganisms [69]. This goal is reached through the secretion of polymer-specific enzymes and free radical generation [66]. Action of extracellular enzymes on a polymer is generally defined as the concept of depolymerization [70]. Biofragmentation could lead to microplastic formation if the plastic media is not assimilated yet by microorganisms [64].

Assimilation

This stage is defined for the real absorption of the plastic atoms into the microbial cell; providing essential needs such as energy, electrons and elementary sources like carbon, nitrogen and phosphorus. Microorganisms are able to sustain and reproduce at the time they produce energy via aerobic respiration, anaerobic respiration or fermentation [66].

As a result of polymer cleavage, monomer/oligomer absorption and metabolic processation; microbes can release mineral molecules, contributing to natural biogeochemical processes, as well as organic molecules, which some could be ecotoxic threats under certain conditions and degrees [66]. Mineralization differs by the presence of carbon dioxide and water under aerobic conditions, and methane and carbon dioxide for anaerobic [67].

Some byproducts laid by microbial metabolic activity through the biodegradation process could have potential use for other technological or industrial uses and applications [71].

The chemical reactions resulting from plastic biodegradation through aerobic and anaerobic respiration are illustrated by Equation 1 and Equation 2.



Equation 1. Aerobic microbial biodegradation of plastic [72].



Equation 2. Anaerobic microbial biodegradation of plastic [72].

Aerobic microbial biodegradation of plastics (Equation 1) is performed by the use of oxygen as electron acceptor, breaking down organic chemicals into smaller organic compounds or monomers. Carbon dioxide and water are excreted as byproducts of the cleavage. Meanwhile, in anaerobic microbial biodegradation (Equation 2), microbes set nitrate, sulphate, iron, manganese and carbon dioxide as electron acceptors due to lack of oxygen for the cleavage and formation of smaller compounds [72].

All these stages of the general biodegradation process of plastic through microbial activity are illustrated in Figure 1.

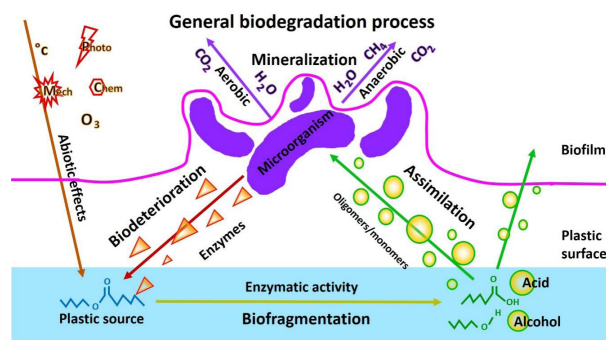


Figure 1. General biodegradation process by microorganisms. The three stages of biodeterioration are illustrated as detailed previously in this review. Note that the Chem, Mech, Photo, °C and O₃ symbols represent Chemical degradation, Mechanical degradation, photodegradation, temperature and Ozone, as they are abiotic drivers for plastic degradation on the environment.

6. Conclusions

Some remarkable features about the state of the art is that bacterial strains come mostly from the bias to the human environment, rather than natural ecosystems. Waste and trash disposal sites, recycling sites, city soil samples and laboratory or purchased strains are the most common origins for plastic degrading bacteria. Otherwise, if natural environments are also well covered, most research papers focus on marine environments, mainly in seawater exposure experiments, leaving a great research gap and an opportunity for studies on coastal and wetland environments, considering that these ecosystems have great biodiversity.

Microbial biodegradation of plastic is known to be an environmentally friendly, cheap and acceptable way for plastic waste treatment [29], so waste management actions should pay some attention to these potential opportunities.

This knowledge could be applied into technological developments for bioremediation or biomitigation of plastic polluted ecosystems. As well as integrate to municipal waste management plans, which even today are not well designed nor applied to most urban and rural locations.

Incursions into new strategies and solutions to plastic pollution will cause positive impacts on the world's ecosystems and human population, with the participation of every government level, as well as corporations and non-governmental organizations. Some other positive impacts of development and action on this subject rely on the achievement of United Nation's 2030 Sustainable Development Goals. In such objectives as Good Health and well-being, clean water and sanitation, climate action, life below water, life on land and partnerships for the goals. Industrial companies could benefit from economic incen-

tives, positive publicity and product mark-up as a result of extending their value chain responsibility by contributing into plastic-pollution mitigation initiatives.

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Conflict of Interest

The authors have no conflict of interest to declare.

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