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## Combating antibiotic resistance in the human-impacted environment with carbon-based materials : Applications and challenges

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1 **Combating antibiotic resistance in the human-impacted environment**  
2 **with carbon-based materials: Applications and challenges**

3

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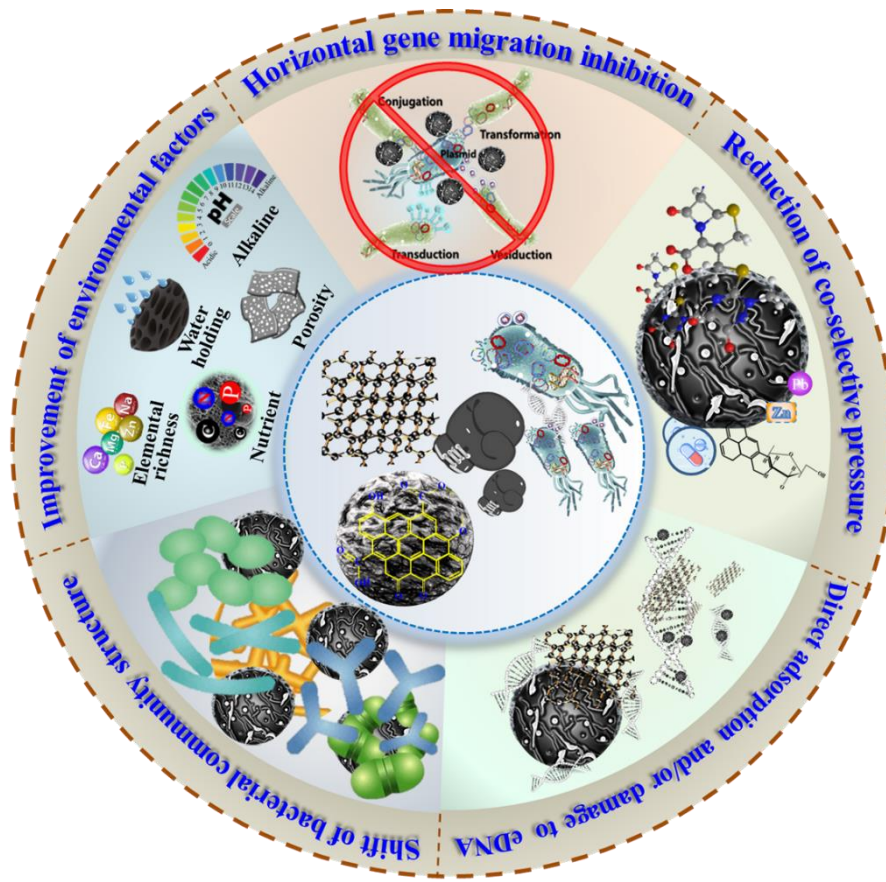
39 **Abstract:** Antibiotic resistance and its dynamics in different environmental  
40 compartments have attracted increasing attention due to potential resistant gene transfer  
41 into human pathogens. Hence, several researchers focused to combat the growing  
42 prevalence of antibiotic resistance genes (ARGs) in diverse environmental media,  
43 wherein various carbon-based amendments can be used to resolve problems with the  
44 emerging contaminants. However, we still lack systematic knowledge on the  
45 performance and mechanisms of carbon-based materials to alleviate ARGs. For that,  
46 carbon-based materials used as additives, amendments, adsorbents or other functional  
47 materials in compost, soil and water environments were summarized. The underlying  
48 mechanisms of alleviating the ARG pollution using carbon-based materials are mainly  
49 related to 1) the improvement of environmental factors, 2) the alteration of microbial  
50 community structure, 3) the reduction of co-selective pressure caused by chemical  
51 contaminants, 4) the decrease of mobile genetic element abundance mediating  
52 horizontal gene transfer processes, and 5) direct adsorption and/or damage to  
53 extracellular DNA. This review aims to enrich the understanding of functional roles of  
54 carbon-based materials, and to provide a basis for developing management strategies  
55 to mitigate ARG pollution.

56

57 **Keywords:** antibiotic resistance genes, carbon-based material, One Health,  
58 environmental ecosystem, impedance process and mechanism

59

60 Graphical abstract:



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88 1. Introduction

89 Antimicrobial drugs, originating from the natural, semisynthetic or synthetic  
90 substances to cure bacterial infections, are the footstone of modern medicine. Global  
91 antibiotic consumption rates significantly rose by 46% in the last two decades,  
92 displaying clear spatial disparities (Browne et al., 2021). As one of the largest producers  
93 and consumers of antibiotics worldwide, China is strictly controlling the use of  
94 antibiotics. However, over half of antibiotic prescriptions is still inappropriate from a  
95 nationwide descriptive database study (Zhao et al., 2021). Imprudent use of these drugs  
96 in medical, agricultural and veterinary sectors accelerates the evolution and spread of  
97 antibiotic resistomes, far beyond the natural speed (Fisher Matthew et al., 2018; Tyers  
98 & Wright, 2019). Behaviors including injudicious sale of antibiotics over-the-counter  
99 for clinical therapy, and discharge of improperly disposed waste emanating from  
100 hospitals, farms and factories, worsen this problem in the environment, resulting in the  
101 proliferation and accumulation of antibiotic-resistant bacteria (ARB) and antibiotic  
102 resistance genes (ARGs) (Wang et al., 2018; Zhu et al., 2013). Various contaminants in  
103 the environment such as heavy metals and disinfection reagents sustain high selection  
104 pressures and promote the transfer of resistance genes (Jechalke et al., 2014), while  
105 tourism and international trade additionally lead to the international distribution of  
106 resistant phenotypes (Singh et al., 2021). Nowadays, antibiotic resistance is happening  
107 seriously, affecting populations in almost any country. It is reported that antibiotic  
108 resistance has caused 1.27 million deaths in 2019, significantly more than HIV or  
109 malaria, and that it may develop into the primary cause of global deaths by 2050 (Knight

110 et al., 2021; Murray et al., 2022). Tripartite organizations, the United Nations  
111 Environment Program, and many global health agencies and researchers have thus  
112 recognized antibiotic resistance as one of the intractable and imminent challenges in  
113 the 21st century, and called for joining forces to strengthen environmental action within  
114 the framework of One Health to deal with antibiotic resistance crisis (CDC, 2019;  
115 UNEP, 2022).

116 Investigation of antibiotic resistance, as a newly emerging threat, is expanding  
117 from epidemiological and clinical contexts to environmental fields, and studies on  
118 mitigating the pollution of antibiotic resistance and remediation technologies are being  
119 actively carried out to decrease the adverse effects (Nadimpalli et al., 2021). An  
120 excellent scientometric tool, CiteSpace, was used to visualize the research advances in  
121 relevant publications from 2010 to 2021 with the topic of “antibiotic resistance &  
122 removal” (Text S1). Studies about the removal of antibiotic resistance were  
123 disseminated across 2568 papers (quantified from “Web of Science Core Collection”  
124 database) with a gradually ascending number of publications year by year (Fig. S1A).  
125 The keyword co-occurring network could be used to monitor the development trends  
126 over time (Yu et al., 2017a), and the keywords under the topic were mainly categorized  
127 into five research areas: ARGs in diverse environmental media, the emergence of ARGs  
128 with co-occurring contaminants, ARG remediation treatments, relationships between  
129 ARGs and potential host bacteria, and others like fate, performance, mechanism etc.  
130 (Fig. S1B, Table S1).

131 The number of studies related to ARG remediation has increased rapidly since

132 2015 (Fig. S1A). Of which, biochar (frequency 46) and graphene oxide (frequency 29),  
133 belonging to carbon-based materials, are high-frequency words in ARG remediation  
134 treatments (Table S1). Carbon-based materials comprise numerous advantages such as  
135 large specific surface area, abundant functional groups, good thermal stability, and  
136 broad-spectrum applicability (Biswal & Balasubramanian, 2022; Duan et al., 2020;  
137 Smith & Rodrigues, 2015). Based on these advantages, carbon-based materials receive  
138 wide attention, and can be applied as environment friendly, economic and easy use for  
139 ARG removal from different environmental media. Already simple biochar  
140 amendments, e.g., from pyrolysis of bamboo significantly reduced the abundance of  
141 ARGs by 43.4% to 51.8% in soil and lettuce leaves (Duan et al., 2017). Graphitic carbon  
142 nitride, as excellent adsorbents with porous structure and large surface area, even  
143 removed ARGs by maximally 4 orders of magnitude to that in the control at pH value  
144 of 2.0 - 7.0 and a wide temperature range of 4-40 °C in water (Zhan et al., 2020). Besides,  
145 carbon-based materials are often used as carriers/skeletons to enhance the advantages  
146 of composites on ARG mitigation. Hierarchical  $\text{Bi}_2\text{O}_2\text{CO}_3$  wrapped with modified  
147 graphene oxide was synthesized to jointly adsorb and inactivate ARB and ARGs (Li et  
148 al., 2020). Given the universality and high-efficiency using carbon-based materials to  
149 control the development of ARGs, a systematic analysis of the existing knowledge in  
150 the recent literatures pertaining to the removal of antibiotic resistance is the aim of our  
151 review paper.

152         So far, some papers have reviewed the positive effects of carbon-based materials  
153 on the fate of various pollutants including pharmaceutical and personal care products,

154 heavy metals, dyes, volatile organic compounds and others in soil, water and air (Biswal  
155 & Balasubramanian, 2022; Duan et al., 2020; Gopinath et al., 2021; Makabenta et al.,  
156 2021). These reviews have summarized and shed light on the development of carbon-  
157 based materials in different environmental applications, enriching the understanding of  
158 carbon-based materials as well as their related research. However, few paper addressed  
159 the alleviation of ARGs in the human-impacted environments and the underlying  
160 mechanisms. To address this issue, this review introduces the pathways of ARG transfer  
161 among microbiota and diverse environments, followed by the processes and related  
162 mechanisms using carbon-based materials in the compost, soil and water to alleviate  
163 the prevalence of ARGs. Finally, the challenges and prospects for future research are  
164 discussed.

165

166 2. Transfer of antibiotic resistance and carbon-based material as the potential  
167 mitigation strategy

168 2.1 Antibiotic resistance dissemination among microbiota

169 Antibiotic resistance is ancient and predates the clinical use of antibiotics (D'Costa  
170 et al., 2011). This intrinsic antibiotic resistance is the ensemble of chromosomal genes  
171 that were involved in intrinsic resistance (Bernardini et al., 2019). Some bacteria can  
172 be intrinsically resistant to antibiotics, e.g., via impermeable membranes and efficient  
173 efflux pumps like the multi-drug resistant phenotype of gram-negative bacteria (Cox &  
174 Wright, 2013). Many bacteria, however, also acquire resistance against antibiotics from  
175 chromosomal mutation genes by vertical gene transfer (VGT) and/or horizontal gene

176 transfer (HGT) between microbiota, even at different genus levels (Blair et al., 2015).  
177 Of these two types of gene transfer, VGT is an inherited process of genetic materials  
178 from parent to offspring through sexual or asexual reproduction, which can gradually  
179 accumulate minor mutations in genome and amplify the variation between the resulting  
180 progeny and their bacterial ancestors (Patangia et al., 2022). Despite the mutation  
181 probability as low as a thousandth, a few typically growing mutants possessing ARGs  
182 may be better to tolerate or proliferate under the pressure of antibiotics than the  
183 predecessors, ultimately becoming the dominant members of the microbial population  
184 (Dantas & Sommer, 2014).

185 HGT, acquiring exogenous DNA encoding ARGs from one type of bacteria to  
186 another that doesn't share an ancestor-descendant relationship, is considered as the  
187 important evolutionary process to drive the development of antibiotic resistance with  
188 four pathways: conjugation, transformation, transduction and vesiduction (Patangia et  
189 al., 2022; Rodriguez-Beltran et al., 2021) (Fig. 1A). Conjugation, known as bacterial  
190 sex, involves the shift of ARG-encoding DNA between bacteria via the structure of  
191 conjugative pili, likely enabling the recipient cells to become immune to the previously  
192 sensitive antibiotics (Wu et al., 2021). Transformation indicates the uptake, integration  
193 and functional expression of free DNA from lysed cells or active secretion by microbes,  
194 which can transmit DNA remnants into the genome of competent cells, even distantly  
195 related species (Winter et al., 2021). Bacteriophages act as the vehicle to swap genetic  
196 material and incorporate gene into the genome of host cells using either generalized or  
197 specialized transduction. Recent studies define vesiduction as the fourth way of

198 horizontal transfer, where the secretion of extracellular vesicles from donor cells  
199 delivers foreign DNA containing ARGs into the cytoplasm of recipient cells to achieve  
200 gene transfer, even though the quantity of the contribution of vesiduction to antibiotic  
201 resistance dissemination still remains obscure (Domingues & Nielsen, 2017; Soler &  
202 Forterre, 2020). Herein, mobile genetic elements (MGEs), such as plasmids, integrons,  
203 gene cassettes, insertion sequences, transposons and bacteriophages, are considered to  
204 be indispensable components for the spread of ARGs via HGT among microbial  
205 populations (Partridge et al., 2018). Comprehensive evidence suggests that genetic  
206 diversity could be circularly acquired by vertical and MGEs-mediated gene transfers in  
207 microbial populations, especially in bacteria with prevalent antibiotic resistance in  
208 diverse environments due to antibiotic abuse.

## 209 2.2 Global transmission of antibiotic resistance among diverse environments

210 Global concerns on the rapid emergence and spread of ARGs are deeply rooted  
211 among the people, as indicated by the increasing spectra of untreatable infections  
212 caused by multidrug-resistant bacteria (Blair et al., 2015; Murray et al., 2022). With the  
213 revelation of linkages between microbial mass movements and global biogeochemical  
214 processes, the recognition of ARGs circulating between human-impacted ecosystems  
215 and natural environmental compartments is gained from a One Health perspective (Fig.  
216 1A) (Tiedje et al., 2019; Zhu et al., 2017).

217 ARGs dynamically shuttle among the microbiomes of plants, animals and humans,  
218 significantly coercing the human health by many routes (Wang et al., 2021). For  
219 example, microorganisms and its ARG-encoding genes can be moved by mechanical

220 forces (e.g., water and air currents) in natural processes, followed by a direct pathway  
221 into human body through drinking water and atmospheric aerosol (Hu et al., 2021; Xie  
222 et al., 2019). Recent studies have revealed that bacteria that constitute the major part of  
223 gut microbiota harbor a variety of ARGs, can function as a reservoir promoting ARG  
224 horizontal transfer from commensal bacteria to gut-resident opportunistic bacteria  
225 (Roche-güe et al., 2021; Zhu et al., 2022). Importantly, the uptake of ARG in  
226 consumption of raw vegetables, edible crops as well as eating meat from food-  
227 producing animals via the food chain accounts for the large contribution of acquiring  
228 ARGs to humans (Chen et al., 2019c; Lambrecht et al., 2019). More seriously, the  
229 development of trade and international integration with convenient traffic and frequent  
230 exchanges forms an unexpected planetary-scale mobilization of ARGs (Singh et al.,  
231 2021). Population mobility via air, land and sea, global transport of goods and products,  
232 and ballast water of ship navigation etc. have been reported to accelerate the speed and  
233 scale of ARG dissemination (Lv et al., 2020; Sridhar et al., 2021; Van Boeckel Thomas  
234 et al., 2019). Changes of global antibiotic resistance have inevitable and flow-on effects  
235 on microbial biogeography and their ecological services (Zhu et al., 2019). However,  
236 the impacts to biogeochemical processes can be hardly evaluated.

237 Chemical contaminants discharged by human activities may be selective agents to  
238 promote the dissemination of ARGs (Jutkina et al., 2018). The range of such  
239 contaminants is large, departing from additional antibiotics or antimicrobial peptides  
240 other than those currently targeted in clinical or therapeutical treatment, and including  
241 several health care products like disinfectant agents (Mulder et al., 2018), engineered

242 nanoparticles with antimicrobial properties (Sharma et al., 2009), as well as several  
243 heavy metals like Cu and Zn commonly used in agriculture, but also Hg or Cd as  
244 common contaminant remains (Chen et al., 2019b; Seiler & Berendonk, 2012).  
245 Exposure to chemical contaminants may be triggered by the antibiotic-like effects on  
246 the diversity and abundance of ARGs (Feng et al., 2021). Noteworthy, due to different  
247 chemical properties of these agents, the exploration of highly efficient technologies for  
248 controlling ARG dissemination is urgently needed for the sustainable development of  
249 human beings and to safeguard the planetary health.

### 250 2.3 The feasibility using carbon-based materials to combat antibiotic resistance

251 As the spread of ARGs is due to both microbial performance and maintenance of  
252 selection pressure, efficient strategies to remove ARGs from environment should  
253 actually target all these drivers. Rising antagonistic potentials by, e.g., improved  
254 agricultural productivity and elevated carbon and energy supply may induce a natural  
255 attenuation of ARG with time (Jechalke et al., 2013), possibly due to lower fitness of  
256 ARB relative to their soil-inherent counterparts (Pérez-Valera et al., 2019). However,  
257 such methods are not efficient if co-contaminants remain. The latter is not trivial,  
258 because contrasting conditions may be needed to immobilize them, such as elevated pH  
259 values for immobilizing heavy metals but low pH values for efficient adsorption of  
260 antibiotics. Carbon-based materials provide an option for all, sequestration of co-  
261 contaminants by diverse chemisorption and physical entrapment processes, direct  
262 bacteriostatic effects or even DNA structural damage (Fig. 1B), or enhanced soil  
263 surfaces for increased biodegradation and growth of organisms with potential

264 antagonistic properties when applied, e.g., as larger biochar particles (Liu et al., 2019),  
265 targeted sorption or provision of other carbon and nutrient sources for altering microbial  
266 community structures (Lehmann et al., 2011). The properties of carbon-based materials  
267 such as organic and inorganic compositions, pH, thermal stability, specific surface area  
268 and porosity structure can vary with diverse feedstocks and preparation methods, and  
269 thus cause various types of carbon-based materials as well as different impacts on  
270 resistome compositions (Huang et al., 2022; Lian et al., 2020; Shao et al., 2022).  
271 Wherein carbon-based materials with size matters (classification by physics) have  
272 distinct effects on the alleviation of ARGs, which might be a critical yet overlooked  
273 factor. Many studies have reported that bulk carbon-based materials are easily split into  
274 nanoscale particles that possess a high mobility, high surface area and abundant oxyl  
275 groups, and can transport from terrestrial to aquatic environments, and thus interacting  
276 with ARGs in different environmental media (Liu et al., 2018; Zha et al., 2022).  
277 Generally, adsorption of chemical contaminants or resistant bacteria/DNA is observed  
278 on the surface of bulk carbon-based materials during the ARG spread processes, while  
279 not only adsorption but also oxidative damage of ARG determinants caused by  
280 persistent free radicals is found to occur on nano carbon-based materials (Lian et al.,  
281 2020; Smith & Rodrigues, 2015; Xiang et al., 2019). The efficiency and success of these  
282 measures, depend, however, on the medium to which the carbon-based materials are  
283 amended (Figs. 2-4).

284

### 285 3. Changes of antibiotic resistance in the compost by adding carbon-based materials

286           Organic wastes (e.g., livestock manure and activated sludge) have been reported  
287 to be rich in diverse and abundant ARGs (Xie et al., 2022). Besides, these wastes can  
288 be rich in several contaminants promoting selection pressure for ARGs and resistant  
289 gene transfer (Chen et al., 2019a; Ostermann et al., 2014). Excessive or even improper  
290 disposal towards those wastes can thus accelerate the proliferation and spread of ARGs  
291 via bioaerosol, sewage or food chain (Cui et al., 2020). Composting, as a  
292 bioremediation technology, entails the bio-decomposition and stabilization of organic  
293 wastes wherein the transient anoxic conditions and elevated temperatures during the  
294 composting process enabling the alleviation or removal of antibiotic residues and ARGs  
295 in manure/sludge so as to achieve stable products as soil amendments (Ezzariai et al.,  
296 2018). The introduction of additives to compost often improves its quality, regarding  
297 nitrogen conservation, odor adsorption, pollutant abatement and microbial succession,  
298 as well as the inhibition of ARG dissemination (Barthod et al., 2018; Shan et al., 2021;  
299 Xiao et al., 2017). Carbon-based additives have widely confirmed the positive effects  
300 on the alleviation of ARGs, which could be divided into two categories: wasted  
301 materials originating from the agricultural/industrial field and reprocessed materials.

302           The utilization of additives with low-cost and extensive-supply attributes, obtained  
303 from the agricultural/industrial wastes, is an important means of waste resource  
304 utilization, and significantly influences the dynamics of ARGs in compost. Coal  
305 gasification slag, as the by-product of the entrained-flow gasification process, is  
306 characterized with high carbon content, abundant porous structure and large specific  
307 surface area (Li et al., 2019b). The amendment of coal gasification slag in swine manure

308 composting effectively intensified the removal of ARGs by enriching the microbial  
309 diversity to relatively reduce the potential pathogenic hosts and restraining the HGT  
310 process via decreasing the abundance of MGEs, wherein addition of 10% coal  
311 gasification slag in compost might be a suitable additive for ARG removal (Lu et al.,  
312 2018). Some related studies also confirmed the positive effect of other raw composting  
313 additives, such as woody peat, lignite and brick granules, however, the contribution to  
314 ARG removal showed limited efficiency (Cao et al., 2020; Huang et al., 2021; Xie et  
315 al., 2021). Specifically, the addition of brick granules failed to effectively decrease the  
316 abundances of antibiotic resistome, which might be attributed to the release of some  
317 unknown components from wasted brick granules that inhibited the microbial growth  
318 and stimulated the propagation of antibiotic resistome (Huang et al., 2021), indicating  
319 that additive quality significantly influences the efficiency of ARG elimination.

320 Exploration for improving the efficiency of composting on the alleviation of ARGs  
321 casts to some reprocessed materials with functional attributes. Biochar, pyrolyzed by  
322 organic biomass and with the attributes of large specific surface area and abundant  
323 functional groups, is known for an excellent compost additive to augment the  
324 composting processes by altering physicochemical conditions, enriching nutrients,  
325 immobilizing toxicants, and finally mitigating the abundances of pathogenic bacteria  
326 and ARGs (Xiao et al., 2017). Compared to non-amended compost, 21.6%-99.5% of  
327 the total abundances including *ermB*, *ermF*, *ermQ*, *ermX*, *sul2*, *drfA1*, *drfA7*, *tetC*, *tetG*,  
328 *tetW*, *tetX*, and *intI1* declined after composting with bamboo biochar (Li et al., 2017).  
329 Recent studies have pointed out that biochar produced by diverse feedstock materials

330 and pyrolysis conditions might significantly impact the fate of antibiotic resistome in  
331 the compost. Actually, the physicochemical properties of biochar, such as carbon  
332 content, thermal stability, element compositions, pH, porosity, are the key factors to  
333 regulate the distribution of antibiotic resistome (Shao et al., 2022). Therefore, more  
334 attention should be paid to systematically analyze the relationship between chemical  
335 and physical properties of biochar and the reduction effects on ARGs. Graphene oxide  
336 with various oxygen-containing functionalities and strong surface chemical activity  
337 was applied to construct a graphene oxide-based aerobic composting that graphene  
338 oxide addition can accelerate compost maturation, reduced nitrogen loss and heavy  
339 metals mobility, which largely reduces the selection pressure towards ARG  
340 proliferation (Li & Song, 2020). Activated carbon, showing a high capacity to adsorb  
341 pollutants, was co-composted with olive mill waste that can significantly immobilize  
342 organic (polycyclic aromatic hydrocarbons) and inorganic (toxic elements)  
343 contaminants and minimize their spread and bioavailability, thus weakening the  
344 prevalence of antibiotic resistance induced by co-selection in the environment (García-  
345 Delgado et al., 2019). Chitosan, derived from shellfish via the deacetylation of chitin,  
346 is used as an emerging alternative to improve antibiotic dissipation during composting  
347 (Mukhtar Ahmed et al., 2020). Chitosan adsorbed antibiotics by ion-exchange and  
348 electrostatic attraction, accompanied by an intensified antibiotic degradation driven by  
349 high temperature in the compost, jointly reducing the risk of ARG dissemination (Liu  
350 et al., 2021a). Except for the application of solid additives, the liquid surfactants (i.e.,  
351 rhamnolipid and Tween 80) containing hydrophobic and lipophilic groups were added

352 to animal manures to investigate their effects on ARGs. After composting, the  
353 abundance of both ARGs and *intI1* was reduced twice as much as the control due to the  
354 decreased bioavailable heavy metals (Zhang et al., 2016). Additionally, researchers are  
355 trying to synthesize polymeric materials to strengthen the alleviation of ARGs in  
356 compost systems. A newly carbon composite was synthesized by a proportional mix of  
357 the phyllosilicate attapulgite and activated carbon, and was applied in compost  
358 contaminated with antibiotics and heavy metals to achieve a fast stabilization of heavy  
359 metals, degradation of antibiotics, as well as the decrease of ARG abundances (Lin et  
360 al., 2021). The commercial superabsorbent polymers (i.e., sodium polyacrylate) with  
361 crosslinked and hydrophilic structures have been reported to be a suitable amendment  
362 that could effectively immobilize heavy metals and remove over 90% of ARGs and  
363 MGEs during composting (Guo et al., 2017). Using high-quality carbon-based additives  
364 to shorten composting duration seems an optimization attempt, however, screening the  
365 additives for producing high-quality products with many benefits including ARG  
366 mitigation should obey a cost-effective point of view, which is of great significance for  
367 further practical application.

368 Mechanisms on ARG alleviation via carbon-based additive application in  
369 composting might be related to 1) the operating conditions of composting process, 2)  
370 the changes in selection pressure exerted by environmental contaminants, 3) the  
371 evolution of antagonistic microbial community, and 4) the mediation of HGT (Fig. 2).  
372 Adding carbon-based materials can directly change the composting status, such as the  
373 extension of duration in thermophilic phase, the formation of intra- and interparticle

374 voids to improve compost aeration, the regulation of moisture content and pH (Barthod  
375 et al., 2018). The improvement of abiotic (e.g., temperature, pH and carbon sources,  
376 and available sites for pollutant adsorption) and biotic (e.g., the activity of degrading  
377 bacteria and microbial diversity) processes caused by the introduction of carbon-based  
378 additives jointly promote the depletion of bioavailable contaminant concentrations, thus  
379 reducing the selection pressure on bacteria (Lin et al., 2021). It should be noted that this  
380 reduction in selection pressure can already be reached when only the bioavailable  
381 portions of the co-occurring contaminants are reduced, such as via entrapment of  
382 persistent compounds in inaccessible voids or precipitation of heavy metals with ashes,  
383 even if total pollutants may still be present at other, non-accessible microsites. Both the  
384 improved composting conditions and reduced selection pressure can finally facilitate  
385 the decay of ARG-host bacteria and the succession of microbial community, thus  
386 decreasing the proliferation of ARGs highly reliant on VGT. The effective removal of  
387 MGEs, strongly associated with the antimicrobial gene transfer, further results in the  
388 reduced frequency of HGT during composting with carbon-based additives (Zhang et  
389 al., 2017). However, much work has confirmed the increase in the abundance and  
390 persistence of some type of ARGs even though they undergo the composting along with  
391 carbon-based additives (Fu et al., 2021c), indicating that more kinds and quantities of  
392 ARGs should be taken into account when deeply excavating the underlying  
393 mechanisms of various carbon-based additives towards ARG alleviation in the  
394 composting in future studies.

395

396 4. Effects of applying carbon-based materials on antibiotic resistance in soil  
397 environment

#### 398 4.1 Amending soil with carbon-based materials to mitigate ARG abundance

399 Soil, harboring substantially diverse microorganisms, serves as the natural and  
400 major reservoir of antibiotic resistome as well as the important receiving pool of ARGs  
401 derived from surface runoff, atmospheric deposition and human and animal wastes  
402 (Tiedje et al., 2019; Wang et al., 2021). Therefore, remediating soil ARG pollution and  
403 reducing human exposure risks are of great urgency given many elusive environmental  
404 perturbations exerted by human pollution. Recently, the utilization of carbon-based  
405 materials into soil environments as a soil amendment to control ARG pollution has  
406 attracted significant attention. Positive impacts of wide biochar application in soil-plant  
407 systems have been authenticated on protecting vegetable safety, reducing abundance of  
408 pathogenic bacteria and ARG levels (Duan et al., 2017; Ye et al., 2016). Except for  
409 using biochar pyrolyzed at high temperature and under limited oxygen conditions,  
410 applying hydrochar produced by hydrothermal carbonization was another attempt to  
411 investigate the dynamics and fate of ARGs in soil systems. Application of  
412 hydrothermally treated lincomycin mycelial residues increased the abundance of  
413 lincomycin resistance genes at first eight days, followed by a decline to the background  
414 level until the 50 days incubation period, accompanied by a markable shift of soil  
415 bacterial composition (Wang et al., 2020). Graphene oxide and other carbon-based  
416 materials (e.g., carbon nanotubes and activate carbon) have been applied in agricultural  
417 soil and for soil remediation through nutrient delivery and the ability to adsorb chemical

418 contaminants (Kabiri et al., 2017; Meynet et al., 2012). However, right now, there is no  
419 definitive conclusions to illustrate their influence on ARG dynamics in soil  
420 environments. To optimize the performance of carbon-based materials on ARG-  
421 contaminated soil, modified methods coupled with functional substances are being  
422 actively explored. A struvite-humic acid loaded biochar/bentonite composite was  
423 fabricated and applied in manured soil, which displayed effective capacities to reduce  
424 37.18% of the total relative abundance of ARGs, and thoroughly eliminate ARB-  
425 *Actinobacteria* (Li et al., 2019a). Similar to other environments, the potential  
426 mechanisms of carbon-based materials as soil amendment to eliminate or reduce the  
427 diversity and abundance of ARGs might be due to (1) the improvement of soil  
428 physiochemical properties such as pH, C/N ratio, porosity, and electrical conductivity  
429 (Lehmann, 2007), thereby affecting the fate of ARGs and ARB in soil environments;  
430 (2) the inhibition of mobility and bioavailability of contaminants that impose the  
431 selective/co-selective pressure on soil microbes (Fu et al., 2021a); and (3) the decreased  
432 abundance of MGEs involved in the HGT process among microbial populations (Shao  
433 et al., 2022) (Fig. 3). In many cases, aforementioned factors possibly contribute to the  
434 attenuation of antibiotic resistance, however, the complexity of soil system associated  
435 with plant cultivation and soil biota impacts the effects of carbon-based materials on  
436 soil resistome (Chen et al., 2019c). In particular the addition of available carbon and  
437 nutrient sources, such as via manure, can promote both microbial growth and related  
438 gene copying and transfer of ARGs, as well as increase the dissemination of (organic)  
439 pollutants (Jechalke et al., 2013). Elucidating related interactions with the addition of

440 carbon-based materials might thus warrant further attention, particularly when  
441 combined with organic waste streams.

#### 442 4.2 Combined remediation using biochar and others on soil ARGs

443 The alleviation of ARG pollution is mostly indexed to biochar when referring to  
444 using carbon-based materials in soil environment. Various types of biochar as soil  
445 amendment to mitigate the dissemination of ARGs have been examined. Data point to  
446 some shortcomings when individual biochar is amended in ARG-polluted soil (Zheng  
447 et al., 2021). Co-application of biochar with others like environmentally-friendly  
448 materials, hyperaccumulators, bacteria and bacteriophage to remediate soil  
449 contaminated with ARGs was tested to investigate the feasibility and performance on  
450 controlling ARG pollution. Both biochar amendment and struvite application as  
451 fertilizers can attenuate the enhancing effects of the migration of resistance gene  
452 cassettes-carried microbiota, and decrease the integron-mediated transfer events (An et  
453 al., 2018). Liquid pyroligneous acid containing multiple components such as carboxylic  
454 acids, aldehydes, pyrones and furan groups, and biochar were co-applied into manured  
455 soils to explore the effects on soil ARG abundance (Zheng et al., 2021). An obvious  
456 counteractive effect on ARG mitigation was observed resulting from the adsorption of  
457 antimicrobial components of liquid pyroligneous acids on biochar (Zheng et al., 2021),  
458 which also underscores the significance of suitable environmentally-friendly material  
459 selection for soil ARG control. Biochar amendment combined with a hyperaccumulator,  
460 *Sedum plumbizincicola*, was used to attenuate the prevalence of soil ARGs in  
461 oxytetracycline and cadmium co-contaminated soil (Fu et al., 2021a). Both biochar

462 amendment and planting *Sedum plumbizincicola* significantly decreased the  
463 bioavailability of cadmium in soil and the transfer of oxytetracycline from soil to  
464 hyperaccumulator tissues, and changed the profiles of ARGs in soil-plant systems by  
465 increasing soil antibiotic resistome but restricting their diffusion to plants (Fu et al.,  
466 2021a). It indicates biochar amendment along with plant cultivation, even a  
467 hyperaccumulators with strong capacities of contaminant tolerance and enrichment,  
468 may be insufficient to achieve the full removal of soil ARG pollution (Chen et al., 2018).  
469 As carriers of ARG spread, bacteria and bacteriophage used to compete/inactivate  
470 potential host/pathogenic bacteria for ARG attenuation may become a newly emerging  
471 biotechnological method. A bacterial-loaded biochar via loading *Herbaspirillum*  
472 *huttiense* (*HHS1*) (a low temperature resistant strain) into waste fungus-chaff based  
473 biochar, was used to remediate the antibiotic-heavy metal co-contaminated soil, of  
474 which 41.9% oxytetracycline and 40.7% enrofloxacin were degraded, 85.5% Cu and  
475 64.4% Zn were immobilized, and some resistance genes and their potential hosts were  
476 reduced (Zhang et al., 2022). Biochar amendment and polyvalent bacteriophage jointly  
477 impede the vertical migration of pathogenic bacteria and the dissipation of ARGs with  
478 the decreased level by 2-6 folds in the undisturbed soil columns (Sun et al., 2019). But  
479 remarkably, it is necessary to construct well-established risk assessment frameworks  
480 and environmental regulatory system before the application of related biotechnologies  
481 to avoid the appearance of uncontrollable ecological risks.

482

483 5. Contribution of carbon-based materials on mitigating the antibiotic resistance in

484 aquatic environment

485         Diverse ARGs have been detected in aquatic environments including surface run-  
486 off, river, lake, groundwater, and sewage and wastewater from livestock production and  
487 aquaculture (Karkman et al., 2018; Pärnänen et al., 2019; Waseem et al., 2017; Zou et  
488 al., 2021). Conventional wastewater disinfection technologies are designed to  
489 deactivate the microorganisms and possess limited efficiency in the control of ARG  
490 pollution (Dodd, 2012). Furthermore, the presence of organic pollutants,  
491 pharmaceuticals and personal care products (PPCPs) and antibiotics, could pose  
492 sustained selective pressure to aggravate the emergence and spread of ARGs  
493 (Chaturvedi et al., 2021). Carbon-based materials, owning numerous advantages for the  
494 removal of chemical and biological contaminants, e.g., reducing the bioavailability of  
495 these organic pollutants by adsorption/degradation to decrease the co-selection or the  
496 directly strong adsorption on biological contaminants (Xiang et al., 2019), can be a  
497 promising means to mitigate the prevalence of ARGs in aquatic environments. Herein,  
498 carbon-based materials, such as graphene oxide, biochar, and other carbon-based  
499 materials (e.g., carbon nanotubes and activate carbon), are highly focused to investigate  
500 the performance and underlying mechanisms on ARG removal.

501 5.1 Performance and underlying mechanisms using graphene oxide to combat  
502 antibiotic resistance

503         Graphene oxide - an oxidized form of graphene - has drawn increasing attention  
504 due to its distinct chemical, structural, electronic and antibacterial properties, and has  
505 been widely used in many fields including the biomedicine, machining, electrocatalysis

506 and environmental remediation (Bonaccorso et al., 2015; Xin et al., 2019). The unique  
507 two-dimensional structure, large surface area, aromatic plane and abundant functional  
508 groups allow graphene oxide to remove many contaminants, such as organic pollutants,  
509 heavy metals, as well as pathogens and related ARGs (Smith & Rodrigues, 2015).  
510 Available mechanistic studies using graphene oxide to remove ARGs from the aquatic  
511 environments mostly concentrated on the direct interaction with extracellular ARG-  
512 encoding DNA (Bytesnikova et al., 2019; Zou et al., 2016). Both horizontal and vertical  
513 binding modes were used to explain the underlying mechanisms on ARG inhibition  
514 (Liu, 2012): the chemical binding between opened base pairs in DNA and graphene  
515 oxide surfaces via aromatic stacking in the high-energy adsorption sites (e.g.,  
516 conjugated  $\pi$ -bonding system and oxygen-containing groups) facilitated ARG  
517 adsorption onto the planes; while hydrophobic functional groups in two-dimensional  
518 graphene oxide nanoparticles can also vertically intercalate into the DNA double helix  
519 structure to construct the DNA-graphene oxide complex, thereby inducing DNA  
520 conformational transfigurations and inhibiting the expression of ARGs (Fig. 4).  
521 Graphene oxide also can inhibit the growth and propagation of bacterial strains in  
522 general via the damage to cell membranes by physical destruction (i.e., sharp edges)  
523 and chemical destruction (e.g., reactive oxygen species and mild cytotoxicity), thus  
524 inhibiting the ARG duplication (Yousefi et al., 2017). Additionally, it efficiently  
525 removes co-occurring chemical pollutants (Fig. 4) and thus graphene oxides reduce  
526 selection pressure as another important pathway to alleviate the prevalence of ARGs  
527 (Baig et al., 2019; Wang & Chen, 2015).

528        When graphene oxide was applied to natural waters, over 80% of ARGs were  
529 effectively removed (Yu et al., 2017b). The removal performance of ARGs by graphene  
530 oxide in such aqueous environments is related to multiple factors involving the  
531 properties of graphene oxide, DNA and environmental systems (Table 1). Lateral sizes  
532 of graphene oxide used ranged from 0.08 to 1.0  $\mu\text{m}^2$ , i.e., it has been mainly used in  
533 nanoparticulate to fine colloidal sizes. These fine particles can intercalate into the DNA  
534 base pairs and induce DNA cleavage and conformational transition. The smaller the  
535 size of the particles, the more efficient they were in damaging bacterial DNA damage  
536 and inhibiting the amplification and transformation of ARGs (Xu et al., 2019). Most  
537 notably, graphene oxide at low concentration could promote the conjugative transfer of  
538 ARGs between bacteria as it increased membrane permeability (Guo & Zhang, 2017).  
539 However, the regulatory concentrations using graphene oxide for antibiotic resistance  
540 promotion or inhibition has not yet been quantified, deserving more detailed research.  
541 Besides, other factors like DNA length, DNA structure and the gene type in contact  
542 affect the binding with graphene oxide. In general, short DNA molecules are more  
543 conducive to the adsorption on the surface of graphene oxide than larger ones (Wu et  
544 al., 2011). Sorption of cyclic-stranded-ARGs depended on the DNA base compositions,  
545 while sorption of double-stranded-ARGs mainly depended on DNA length.  
546 Additionally, DNA bases with high guanine content seemed to have strong and tight  
547 affinity to graphene oxide (Yu et al., 2017b). Finally, environmental factors such as pH,  
548 cation species and temperature influenced interactions between DNA molecules and  
549 graphene oxide and, thus, the fate of ARGs in aqueous environments. Clearly, more

550 research is required to explore the interconnections and mechanisms of graphene oxide  
551 and DNA as well as the potentially relevant interference factors to mitigate the threats  
552 of ARG dissemination in environment.

553 Graphene oxide with versatile properties can also be used as base to fabricate  
554 related multifunctional materials that restrain ARG transfer in aqueous environments.  
555 For example, using graphene oxide and gold nanoparticles with strong adsorption  
556 affinity as well as  $\text{Co}_3\text{O}_4$ , a promising chemotherapy agent, allowed to synthesize the  
557 Au/GO- $\text{Co}_3\text{O}_4$  composite that effectively inhibited the replication of tetracycline  
558 resistance genes via groove binding (Yu et al., 2018). Furthermore, some researchers  
559 stressed potential applications of graphene oxide to the utilization of photocatalysis  
560 (Guo & Tian, 2019; Zhou et al., 2020). Photocatalysts of ternary nanocomposites  
561 consisting of reduced graphene oxide, graphitic carbon nitride and iron oxide were  
562 activated by visible light to completely disintegrate plasmid DNA containing ARGs  
563 through the synergistic effects of photocatalytic activity, relaxation of photogenerated  
564 charge carriers, quenching of electron-hole pairs, photo-Fenton activity and generated  
565 hydroxyl radicals (Saha et al., 2020). Additionally, a heterogeneous photo-Fenton  
566 reaction was developed by coupling nano pyrite and graphene oxide to simultaneously  
567 remove ARGs, ARB and other organic pollutants (sulfamethoxazole, carbamazepine,  
568 diclofenac, and mecoprop) under solar-driven conditions (Ahmed et al., 2022).  
569 However, the ecotoxicity of nano nature make it a potential threat to the aquatic  
570 environment from a long-term viewpoint, still deserving safety assessments before the  
571 application of (modified) graphene oxide.

572 5.2 Performance and underlying mechanisms using biochar to combat antibiotic  
573 resistance

574 Porous biochar as a promising material for water treatment can directly adsorb the  
575 carriers of ARGs, i.e., extracellular DNA and bacterial cells (Huang et al., 2022). The  
576 adsorption of plasmids on biochar, and the co-immobilization of bacteria cells can  
577 decrease the contact between DNA and receptors, thus restraining the occurrence of  
578 transformation. Particular dispersed biochar particles (nano biochar) could trigger an  
579 intramolecular condensation of plasmids, and damage the cell membrane permeability  
580 of receptors, therewith potentially leading to the inhibition of transformation (Fang et  
581 al., 2022) (Fig. 4). The additional presence of cationic electrolytes (e.g.,  $\text{Ca}^{2+}$  and  $\text{Na}^{+}$ )  
582 can foster the interactions between biochar and extracellular DNA via cation bridging  
583 and increased effective adsorptive sites, thus reducing the possibility of an access to  
584 free DNA into receptors (Fu et al., 2021b).

585 In addition to reports on biochar on ARG transfer via transformation, there are also  
586 indications that conjugative transfer of ARGs is mediated by dispersed colloidal  
587 biochar at low concentrations ( $\leq 10$  mg/L) (Liu et al., 2021b). The process was  
588 promoted by formation of humic-like substances but hampered when the concentrations  
589 of colloidal biochar exceeded 10 mg/L. In similar manner, low concentrations of  $\text{Cu}^{2+}$   
590 at 0.05 mg/L promoted conjugative transfer efficiency, almost two times higher than  
591 the control treatment, whereas high concentrations  $> 0.5$  mg/L inhibited it (Liu et al.,  
592 2022). Whether similar considerations also valid for ARG transfer processes via  
593 transduction and vesiduction remain to be clarified.

594 The use of biochar in aqueous systems has the advantage that it can exploit several  
595 other multifunctional material (Wu et al., 2022). For instance, magnetic biochar with  
596 additions of quaternary phosphonium salts and iron oxides displayed high efficiencies  
597 in deactivating bacteria and bacterial DNA, thus in suppressing the ARG spread (Fu et  
598 al., 2021b; Fu et al., 2020), as, e.g., shown in applications to livestock wastewater (Fu  
599 et al., 2022). Using  $\beta$ -cyclodextrin functionalized biochar for co-contaminated  
600 wastewater even helped to additionally reduce heavy metal contaminations down to <  
601 0.05 mg/L; methyl orange was even removed by up to 98.8%. Correspondingly, with  
602 the decline in co-selective pressure, the abundances of typical ARGs in the wastewaters  
603 declined by 49% to 91% relative to the controls (Wu et al., 2020). In general, there is  
604 growing evidence in mitigating the diversity and abundance of ARGs using (modified)  
605 biochar, even though current studies are still insufficient in revealing the related  
606 impedance mechanisms.

### 607 5.3 Performance and underlying mechanisms using other carbon-based materials to 608 combat antibiotic resistance

609 Other carbon-based materials such as carbon nanotubes and activated carbon are  
610 popularly used in aquatic environments for contamination control, due to their large  
611 surface area and porosity, and thermal stability for modification (Xiang et al., 2019).  
612 Carbon nanotubes added to a sequencing batch bioreactor were found to destabilize  
613 bacterial population structure and microbial physiological status in effluents, and  
614 facilitate the removal of ARGs in subsequent disinfection process (Wang et al., 2022).  
615 Interestingly, attributed to the size, simple application of these carbonaceous materials

616 with large particle sizes, like granular activated carbon, even enhance the bacterial  
617 biomass, becoming the hotbed of ARG proliferation (Su et al., 2018). In this regard,  
618 fabricated carbon-based functional materials with antibacterial effects earn much  
619 attention. For example, granular activated carbon modified by  $\text{Fe}_2\text{O}_3$  effectively  
620 inhibited bacterial growth, biofilm aggregation and overall microbial metabolism,  
621 resulting in a sustained inhibition of resistance genes in simulated drinking water  
622 distribution systems (Li et al., 2022). Carbon nanotube was used as a base to conjugate  
623 with tetragonal bismuth vanadate and monoclinic bismuth vanadate to synthesize a new  
624 photocatalyst, which had an excellent ability to generate  $\bullet\text{O}_2^-$ ,  $\text{h}^+$  and  $\bullet\text{OH}$  for  
625 photocatalytic inactivation against the antibiotic-resistant pathogen and ARGs in real  
626 wastewater (Ye et al., 2021). Except for the modification of carbon-based materials,  
627 combined processes composed of these materials are frequent used in water treatments.  
628 An electrified carbon nanotube membrane was combined with chlorine disinfection (i.e.,  
629  $\text{NaClO}$ ) could inactivate ARB and damage ARGs by generated reactive oxygen species  
630 ( $\bullet\text{O}_2^-$  and  $\bullet\text{OH}$ ) (Wang et al., 2023). Activated carbon doped with ferromagnetic oxide  
631 was coupled with ultrafiltration to synergistically reduce the ARB, ARGs and dissolved  
632 effluent organic matter in reclaimed water, of which magnetic activated carbon can be  
633 easily separated from aquatic solutions, avoiding secondary pollution (Tan et al., 2022).  
634 Much work has been done in exploring the performance using carbon nanotubes and  
635 activated carbon in ARG removal, however, the utilization of coupled frameworks may  
636 deserve further research as compared to a solitary treatment technology.

637

## 638 6. Conclusions and future perspectives

639 Presently, the global concerns of rapid emergence and proliferation of antibiotic  
640 resistance due to extensive and misuse of antibiotics are increasing. Growing evidence  
641 has reported that ARGs can spread antibiotic resistance via VGT and HGT between  
642 bacterial populations. The effectiveness of carbon-based materials to alleviate these  
643 risks when used as additives, amendments, adsorbents or other functional materials in  
644 different environmental media has been substantially documented. The key  
645 mechanisms of alleviating the ARG pollution using carbon-based materials are mainly  
646 related to 1) the general alteration of microbial community structure, 2) the reduction  
647 of co-selective pressure caused by chemical contaminants, 3) the decrease of MGE  
648 abundance mediating HGT processes, 4) direct adsorption and/or damage to  
649 extracellular DNA, and 5) the improvement of environmental factors affecting DNA  
650 binding or ecological competition by non-resistant bacterial strains. Overall, carbon-  
651 based materials could assist us in combatting antibiotic resistance and related  
652 mechanisms as needed to intellectually confront global healthcare crisis and to remove  
653 ARG pollution. However, some key knowledge gaps on how to systematically and  
654 safely use carbon-based materials to reach these aims should be underscored and filled  
655 in the future.

656 (1) An increasing body of studies evidenced the dissemination of ARGs via the  
657 routes of airborne bioaerosols in indoor and outdoor environments (He et al., 2021; Jin  
658 et al., 2021). ARGs adsorbed on bioaerosols within the pollution area can constitute  
659 atmospheric circulation via wind and evaporation, even enter into human respiratory

660 systems through inhalation, especially for the populations in the high-danger areas like  
661 livestock farms, landfills, wastewater treatment plants and hospitals (Li et al., 2018).  
662 However, to date, research scope attending to remove the airborne ARGs by air  
663 filtration systems is still limited, let alone the development of air filtration system  
664 assisted with carbon-based materials, which deserves more attention in the future.

665 (2) Current studies have reported the excellent performance of carbon-based  
666 materials on the elimination or attenuation of ARGs in the environments, however, the  
667 limitations of each technology should be systematically evaluated. Given the growing  
668 burden of antibiotic resistance and deficiencies relying on single remediation  
669 technology, research and development of combined remediation technologies towards  
670 combating the antibiotic resistance crisis will be a promising and significant project.

671 (3) Most studies lay particular stress on the effects of ARG removal, however,  
672 neglecting the consideration of persistence and regrowth of ARGs under the new  
673 balance with the addition of carbon-based materials. The application of carbon-based  
674 materials aims to strengthen the attenuation of ARGs by passivation, adsorption or  
675 interactions with contaminants, however, whether there will be a long-term and chronic  
676 stress in the carbon-based materials as secondary pollution source to enable the  
677 regrowth or extend the durability of ARGs is still elusive so far.

678 (4) Given the complex components, endogenous pollutants originating from the  
679 carbon-based materials could be a hidden trouble to be introduced into the ecosystems.  
680 Additionally, size matter of carbon-based materials in nanoscale with the nature of  
681 facile mobilization, toxic effects to humans, high instability and accumulation limits

682 their environmental promotion. Therefore, the priority before the wide application of  
683 carbon-based materials is to conduct a detailed and comprehensive assessment.

684 (5) Extensive research has reported the feasibility and efficacy of (modified)  
685 carbon-based materials on the removal of ARGs in human-impacted environments, but  
686 the consideration of economic aspects is scarce. High-quality carbon-based products  
687 fabricated from laboratory often effectively combat the prevalence of antibiotic  
688 resistance, however, the complex production process and high cost may limit their  
689 practically large-scale applications. Therefore, while developing carbon-based  
690 materials in different environmental ecosystems to curb ARG pollution, trade-offs  
691 between efficiency and economy remain to be valued.

692

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701

### 702 **References**

703 Ahmed, Y., Zhong, J., Wang, Z., Wang, L., Yuan, Z., Guo, J. 2022. Simultaneous removal of antibiotic  
704 resistant bacteria, antibiotic resistance genes, and micropollutants by FeS<sub>2</sub>@GO-based

705 heterogeneous photo-Fenton process. *Environmental Science & Technology*, **56**(21), 15156–  
706 15166.

707 An, X., Chen, Q., Zhu, D., Su, J. 2018. Distinct effects of struvite and biochar amendment on the class 1  
708 integron antibiotic resistance gene cassettes in phyllosphere and rhizosphere. *Science of The  
709 Total Environment*, **631-632**, 668-676.

710 Baig, N., Ihsanullah, Sajid, M., Saleh, T.A. 2019. Graphene-based adsorbents for the removal of toxic  
711 organic pollutants: A review. *Journal of Environmental Management*, **244**, 370-382.

712 Barthod, J., Rumpel, C., Dignac, M.-F. 2018. Composting with additives to improve organic amendments.  
713 A review. *Agronomy for Sustainable Development*, **38**(2), 17.

714 Bernardini, A., Cuesta, T., Tomás, A., Bengoechea, J.A., Martínez, J.L., Sánchez, M.B. 2019. The  
715 intrinsic resistome of *Klebsiella pneumoniae*. *International Journal of Antimicrobial Agents*,  
716 **53**(1), 29-33.

717 Biswal, B.K., Balasubramanian, R. 2022. Adsorptive removal of sulfonamides, tetracyclines and  
718 quinolones from wastewater and water using carbon-based materials: Recent developments and  
719 future directions. *Journal of Cleaner Production*, **349**, 131421.

720 Blair, J.M.A., Webber, M.A., Baylay, A.J., Ogbolu, D.O., Piddock, L.J.V. 2015. Molecular mechanisms  
721 of antibiotic resistance. *Nature Reviews Microbiology*, **13**(1), 42-51.

722 Bonaccorso, F., Colombo, L., Yu, G., Stoller, M., Tozzini, V., Ferrari, A.C., Ruoff, R.S., Pellegrini, V.  
723 2015. Graphene, related two-dimensional crystals, and hybrid systems for energy conversion  
724 and storage. *Science*, **347**(6217).

725 Browne, A.J., Chipeta, M.G., Haines-Woodhouse, G., Kumaran, E.P.A., Hamadani, B.H.K., Zarea, S.,  
726 Henry, N.J., Deshpande, A., Reiner, R.C., Jr., Day, N.P.J., Lopez, A.D., Dunachie, S., Moore,  
727 C.E., Stergachis, A., Hay, S.I., Dolecek, C. 2021. Global antibiotic consumption and usage in  
728 humans, 2000-18: a spatial modelling study. *The Lancet Planetary Health*, **5**(12), e893-e904.

729 Bytesnikova, Z., Richtera, L., Smerkova, K., Adam, V. 2019. Graphene oxide as a tool for antibiotic-  
730 resistant gene removal: A review. *Environmental Science and Pollution Research* **26**(20),  
731 20148-20163.

732 Cao, Y., Hu, H., Guo, H., Butterly, C., Bai, M., Zhang, Y., Chen, D., He, J. 2020. Lignite as additives  
733 accelerates the removal of antibiotic resistance genes during poultry litter composting.  
734 *Bioresource Technology*, **315**, 123841.

735 CDC, U.C.f.D.C.a.P. 2019. Antibiotic resistance threats in the United States, 2019. *US Department of  
736 Health and Human Services, Atlanta, GA*, [https://www.cdc.gov/drugresistance/pdf/threats-  
737 report/2019-ar-threats-report-508.pdf](https://www.cdc.gov/drugresistance/pdf/threats-report/2019-ar-threats-report-508.pdf).

738 Chaturvedi, P., Shukla, P., Giri, B.S., Chowdhary, P., Chandra, R., Gupta, P., Pandey, A. 2021. Prevalence  
739 and hazardous impact of pharmaceutical and personal care products and antibiotics in  
740 environment: A review on emerging contaminants. *Environmental Research*, **194**, 110664.

741 Chen, C., Pankow, C.A., Oh, M., Heath, L.S., Zhang, L., Du, P., Xia, K., Pruden, A. 2019a. Effect of  
742 antibiotic use and composting on antibiotic resistance gene abundance and resistome risks of  
743 soils receiving manure-derived amendments. *Environment International*, **128**, 233-243.

744 Chen, J., Li, J., Zhang, H., Shi, W., Liu, Y. 2019b. Bacterial heavy-metal and antibiotic resistance genes  
745 in a copper tailing dam area in Northern China. *Frontiers in Microbiology*, **10**, 1916.

746 Chen, Q., Cui, H., Su, J., Penuelas, J., Zhu, Y. 2019c. Antibiotic resistomes in plant microbiomes. *Trends  
747 in Plant Science*, **24**(6), 530-541.

748 Chen, Q., Fan, X., Zhu, D., An, X., Su, J., Cui, L. 2018. Effect of biochar amendment on the alleviation

749 of antibiotic resistance in soil and phyllosphere of *Brassica chinensis* L. *Soil Biology and*  
750 *Biochemistry*, **119**, 74-82.

751 Cox, G., Wright, G.D. 2013. Intrinsic antibiotic resistance: Mechanisms, origins, challenges and  
752 solutions. *International Journal of Medical Microbiology*, **303**(6), 287-292.

753 Cui, G., Lü, F., Zhang, H., Shao, L., He, P. 2020. Critical insight into the fate of antibiotic resistance  
754 genes during biological treatment of typical biowastes. *Bioresource Technology*, **317**, 123974.

755 D'Costa, V.M., King, C.E., Kalan, L., Morar, M., Sung, W.W.L., Schwarz, C., Froese, D., Zazula, G.,  
756 Calmels, F., Debruyne, R., Golding, G.B., Poinar, H.N., Wright, G.D. 2011. Antibiotic  
757 resistance is ancient. *Nature*, **477**(7365), 457-461.

758 Dantas, G., Sommer, M.O.A. 2014. How to fight back against antibiotic resistance. *American Scientist*,  
759 **102**(1), 42-51.

760 Dodd, M.C. 2012. Potential impacts of disinfection processes on elimination and deactivation of  
761 antibiotic resistance genes during water and wastewater treatment. *Journal of Environmental*  
762 *Monitoring* **14**(7), 1754-1771.

763 Domingues, S., Nielsen, K.M. 2017. Membrane vesicles and horizontal gene transfer in prokaryotes.  
764 *Current Opinion in Microbiology*, **38**, 16-21.

765 Duan, C., Ma, T., Wang, J., Zhou, Y. 2020. Removal of heavy metals from aqueous solution using carbon-  
766 based adsorbents: A review. *Journal of Water Process Engineering*, **37**, 101339.

767 Duan, M., Li, H., Gu, J., Tuo, X., Sun, W., Qian, X., Wang, X. 2017. Effects of biochar on reducing the  
768 abundance of oxytetracycline, antibiotic resistance genes, and human pathogenic bacteria in soil  
769 and lettuce. *Environmental Pollution*, **224**, 787-795.

770 Ezzariai, A., Hafidi, M., Khadra, A., Aemig, Q., El Fels, L., Barret, M., Merlina, G., Patureau, D., Pinelli,  
771 E. 2018. Human and veterinary antibiotics during composting of sludge or manure: Global  
772 perspectives on persistence, degradation, and resistance genes. *Journal of Hazardous Materials*,  
773 **359**, 465-481.

774 Fang, J., Jin, L., Meng, Q., Shan, S., Wang, D., Lin, D. 2022. Biochar effectively inhibits the horizontal  
775 transfer of antibiotic resistance genes via transformation. *Journal of Hazardous Materials*, **423**,  
776 127150.

777 Feng, G., Huang, H., Chen, Y. 2021. Effects of emerging pollutants on the occurrence and transfer of  
778 antibiotic resistance genes: A review. *Journal of Hazardous Materials*, **420**, 126602.

779 Fisher Matthew, C., Hawkins Nichola, J., Sanglard, D., Gurr Sarah, J. 2018. Worldwide emergence of  
780 resistance to antifungal drugs challenges human health and food security. *Science*, **360**(6390),  
781 739-742.

782 Fu, Y., Jia, M., Wang, F., Wang, Z., Mei, Z., Bian, Y., Jiang, X., Virta, M., Tiedje, J.M. 2021a. Strategy  
783 for mitigating antibiotic resistance by biochar and hyperaccumulators in cadmium and  
784 oxytetracycline co-contaminated soil. *Environmental Science & Technology*, **55**(24), 16369-  
785 16378.

786 Fu, Y., Wang, F., Sheng, H., Hu, F., Wang, Z., Xu, M., Bian, Y., Jiang, X., Tiedje, J.M. 2021b. Removal  
787 of extracellular antibiotic resistance genes using magnetic biochar/quaternary phosphonium salt  
788 in aquatic environments: A mechanistic study. *Journal of Hazardous Materials*, **411**, 125048.

789 Fu, Y., Wang, F., Sheng, H., Xu, M., Liang, Y., Bian, Y., Hashsham, S.A., Jiang, X., Tiedje, J.M. 2020.  
790 Enhanced antibacterial activity of magnetic biochar conjugated quaternary phosphonium salt.  
791 *Carbon*, **163**, 360-369.

792 Fu, Y., Zhang, A., Guo, T., Zhu, Y., Shao, Y. 2021c. Biochar and hyperthermophiles as additives

793 accelerate the removal of antibiotic resistance genes and mobile genetic elements during  
794 composting. *Materials*, **14**(18), 5428.

795 Fu, Y., Wang, F., Wang, Z., Mei, Z., Jiang, X., Schäffer, A., Virta, M., Tiedje, J.M. 2022. Application of  
796 magnetic biochar/quaternary phosphonium salt to combat the antibiotic resistome in livestock  
797 wastewater. *Science of The Total Environment*, **811**, 151386.

798 García-Delgado, C., Fresno, T., Rodríguez-Santamaría, J.J., Diaz, E., Mohedano, A.F., Moreno-Jimenez,  
799 E. 2019. Co-application of activated carbon and compost to contaminated soils: toxic elements  
800 mobility and PAH degradation and availability. *International Journal of Environmental Science  
801 and Technology*, **16**(2), 1057-1068.

802 Gopinath, K.P., Vo, D.-V.N., Gnana Prakash, D., Adithya Joseph, A., Viswanathan, S., Arun, J. 2021.  
803 Environmental applications of carbon-based materials: A review. *Environmental Chemistry  
804 Letters*, **19**(1), 557-582.

805 Guo, A., Gu, J., Wang, X., Zhang, R., Yin, Y., Sun, W., Tuo, X., Zhang, L. 2017. Effects of superabsorbent  
806 polymers on the abundances of antibiotic resistance genes, mobile genetic elements, and the  
807 bacterial community during swine manure composting. *Bioresource Technology*, **244**, 658-663.

808 Guo, M.T., Zhang, G.S. 2017. Graphene oxide in the water environment could affect tetracycline-  
809 antibiotic resistance. *Chemosphere*, **183**, 197-203.

810 Guo, M., Tian, X. 2019. Impacts on antibiotic-resistant bacteria and their horizontal gene transfer by  
811 graphene-based TiO<sub>2</sub>&Ag composite photocatalysts under solar irradiation. *Journal of  
812 Hazardous Materials*, **380**, 120877.

813 He, T., Jin, L., Xie, J., Yue, S., Fu, P., Li, X. 2021. Intracellular and extracellular antibiotic resistance  
814 genes in airborne PM<sub>2.5</sub> for respiratory exposure in urban areas. *Environmental Science &  
815 Technology Letters*, **8**(2), 128-134.

816 Hu, Y., Jiang, L., Sun, X., Wu, J., Ma, L., Zhou, Y., Lin, K., Luo, Y., Cui, C. 2021. Risk assessment of  
817 antibiotic resistance genes in the drinking water system. *Science of The Total Environment*, **800**,  
818 149650.

819 Huang, H., Huang, D., Chen, S., Wang, G., Chen, Y., Tao, J., Chen, H., Gao, L. 2022. Removing antibiotic  
820 resistance genes under heavy metal stress with carbon-based materials and clay minerals: By  
821 sorption alone? *Chemical Engineering Journal*, **446**, 137121.

822 Huang, X., Tian, S., Zheng, J., Xu, K., Liu, C. 2021. Fitness reduction of antibiotic resistome by an extra  
823 carbon source during swine manure composting. *Environmental Pollution*, **277**, 116819.

824 Jechalke, S., Heuer, H., Siemens, J., Amelung, W., Smalla, K. 2014. Fate and effects of veterinary  
825 antibiotics in soil. *Trends in Microbiology*, **22**(9), 536-545.

826 Jechalke, S., Kopmann, C., Rosendahl, I., Groeneweg, J., Weichelt, V., Kroegerrecklenfort, E., Brandes,  
827 N., Nordwig, M., Ding, G.-C., Siemens, J., Heuer, H., Smalla, K. 2013. Increased abundance  
828 and transferability of resistance genes after field application of manure from sulfadiazine-  
829 treated pigs. *Applied and Environmental Microbiology*, **79**(5), 1704-1711.

830 Jin, L., Xie, J., He, T., Wu, D., Li, X. 2021. Airborne transmission as an integral environmental dimension  
831 of antimicrobial resistance through the “One Health” lens. *Critical Reviews in Environmental  
832 Science and Technology*, 1-22.

833 Jutkina, J., Marathe, N.P., Flach, C.F., Larsson, D.G.J. 2018. Antibiotics and common antibacterial  
834 biocides stimulate horizontal transfer of resistance at low concentrations. *Science of The Total  
835 Environment*, **616-617**, 172-178.

836 Kabiri, S., Degryse, F., Tran, D.N.H., da Silva, R.C., McLaughlin, M.J., Losic, D. 2017. Graphene oxide:

837 A new carrier for slow release of plant micronutrients. *ACS Applied Materials & Interfaces*,  
838 **9**(49), 43325-43335.

839 Karkman, A., Do, T.T., Walsh, F., Virta, M.P.J. 2018. Antibiotic-resistance genes in waste water. *Trends*  
840 *in Microbiology*, **26**(3), 220-228.

841 Knight, G.M., Glover, R.E., McQuaid, C.F., Oлару, I.D., Gallandat, K., Leclerc, Q.J., Fuller, N.M.,  
842 Willcocks, S.J., Hasan, R., van Kleef, E., Chandler, C.I.R. 2021. Antimicrobial resistance and  
843 COVID-19: Intersections and implications. *eLife*, **10**, e64139.

844 Lambrecht, E., Van Coillie, E., Van Meervenne, E., Boon, N., Heyndrickx, M., Van de Wiele, T. 2019.  
845 Commensal *E. coli* rapidly transfer antibiotic resistance genes to human intestinal microbiota  
846 in the Mucosal Simulator of the Human Intestinal Microbial Ecosystem (M-SHIME).  
847 *International Journal of Food Microbiology*, **311**, 108357.

848 Lehmann, J. 2007. A handful of carbon. *Nature*, **447**(7141), 143-144.

849 Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D. 2011. Biochar effects  
850 on soil biota – A review. *Soil Biology and Biochemistry*, **43**(9), 1812-1836.

851 Li, D., Yu, P., Zhou, X., Kim, J.-H., Zhang, Y., Alvarez, P.J.J. 2020. Hierarchical Bi<sub>2</sub>O<sub>2</sub>CO<sub>3</sub> wrapped with  
852 modified graphene oxide for adsorption-enhanced photocatalytic inactivation of antibiotic  
853 resistant bacteria and resistance genes. *Water Research*, **184**, 116157.

854 Li, H., Duan, M., Gu, J., Zhang, Y., Qian, X., Ma, J., Zhang, R., Wang, X. 2017. Effects of bamboo  
855 charcoal on antibiotic resistance genes during chicken manure composting. *Ecotoxicology and*  
856 *Environmental Safety*, **140**, 1-6.

857 Li, J., Cao, J., Zhu, Y., Chen, Q., Shen, F., Wu, Y., Xu, S., Fan, H., Da, G., Huang, R., Wang, J., de Jesus,  
858 A.L., Morawska, L., Chan, C.K., Peccia, J., Yao, M. 2018. Global survey of antibiotic resistance  
859 genes in air. *Environmental Science & Technology*, **52**(19), 10975-10984.

860 Li, J., Song, N. 2020. Graphene oxide-induced variations in the processing performance, microbial  
861 community dynamics and heavy metal speciation during pig manure composting. *Process*  
862 *Safety and Environmental Protection*, **136**, 214-222.

863 Li, Y., Wang, X., Li, J., Wang, Y., Song, J., Xia, S., Jing, H., Zhao, J. 2019a. Effects of struvite-humic  
864 acid loaded biochar/bentonite composite amendment on Zn(II) and antibiotic resistance genes  
865 in manure-soil. *Chemical Engineering Journal*, **375**, 122013.

866 Li, Z., Li, T., Xing, X., Bi, Z., Qi, P., Hu, C., Xu, G., Chen, C., Ma, K., Chen, J. 2022. Inhibiting the  
867 increase of antibiotic resistance genes during drinking water distribution by superior microbial  
868 interface using Fe modified granular activated carbon. *Journal of Cleaner Production*, **335**,  
869 130225.

870 Li, Z., Zhang, Y., Zhao, H., Chen, H., He, R. 2019b. Structure characteristics and composition of  
871 hydration products of coal gasification slag mixed cement and lime. *Construction and Building*  
872 *Materials*, **213**, 265-274.

873 Lian, F., Yu, W., Zhou, Q., Gu, S., Wang, Z., Xing, B. 2020. Size matters: Nano-biochar triggers  
874 decomposition and transformation inhibition of antibiotic resistance genes in aqueous  
875 environments. *Environmental Science & Technology*, **54**(14), 8821-8829.

876 Lin, H., Sun, W., Yu, Y., Ding, Y., Yang, Y., Zhang, Z., Ma, J. 2021. Simultaneous reductions in antibiotics  
877 and heavy metal pollution during manure composting. *Science of The Total Environment*, **788**,  
878 147830.

879 Liu, G., Zheng, H., Jiang, Z., Zhao, J., Wang, Z., Pan, B., Xing, B. 2018. Formation and physicochemical  
880 characteristics of nano biochar: Insight into chemical and colloidal stability. *Environmental*

881 *Science & Technology*, **52**(18), 10369-10379.

882 Liu, H., Ye, X., Chen, S., Sun, A., Duan, X., Zhang, Y., Zou, H., Zhang, Y. 2021a. Chitosan as additive  
883 affects the bacterial community, accelerates the removals of antibiotics and related resistance  
884 genes during chicken manure composting. *Science of The Total Environment*, **792**, 148381.

885 Liu, J. 2012. Adsorption of DNA onto gold nanoparticles and graphene oxide: surface science and  
886 applications. *Physical Chemistry Chemical Physics*, **14**(30), 10485-10496.

887 Liu, X., Wang, D., Tang, J., Liu, F., Wang, L. 2021b. Effect of dissolved biochar on the transfer of  
888 antibiotic resistance genes between bacteria. *Environmental Pollution*, **288**, 117718.

889 Liu, X.M., Wang, D., Wang, L., Tang, J.C. 2022. Dissolved biochar eliminates the effect of Cu(II) on the  
890 transfer of antibiotic resistance genes between bacteria. *Journal of Hazardous Materials*, **424**,  
891 127251.

892 Liu, Z., Zhu, M., Wang, J., Liu, X., Guo, W., Zheng, J., Bian, R., Wang, G., Zhang, X., Cheng, K., Liu,  
893 X., Li, L., Pan, G. 2019. The responses of soil organic carbon mineralization and microbial  
894 communities to fresh and aged biochar soil amendments. *Global Change Biology Bioenergy*,  
895 **11**(12), 1408-1420.

896 Lu, C., Gu, J., Wang, X., Liu, J., Zhang, K., Zhang, X., Zhang, R. 2018. Effects of coal gasification slag  
897 on antibiotic resistance genes and the bacterial community during swine manure composting.  
898 *Bioresource Technology*, **268**, 20-27.

899 Lv, B., Cui, Y., Tian, W., Wei, H., Chen, Q., Liu, B., Zhang, D., Xie, B. 2020. Vessel transport of antibiotic  
900 resistance genes across oceans and its implications for ballast water management. *Chemosphere*,  
901 **253**, 126697.

902 Makabenta, J.M.V., Nabawy, A., Li, C.-H., Schmidt-Malan, S., Patel, R., Rotello, V.M. 2021.  
903 Nanomaterial-based therapeutics for antibiotic-resistant bacterial infections. *Nature Reviews*  
904 *Microbiology*, **19**(1), 23-36.

905 Meynet, P., Hale, S.E., Davenport, R.J., Cornelissen, G., Breedveld, G.D., Werner, D. 2012. Effect of  
906 activated carbon amendment on bacterial community structure and functions in a PAH impacted  
907 urban soil. *Environmental Science & Technology*, **46**(9), 5057-5066.

908 Mukhtar Ahmed, K.B., Khan, M.M.A., Siddiqui, H., Jahan, A. 2020. Chitosan and its oligosaccharides,  
909 a promising option for sustainable crop production - a review. *Carbohydrate Polymers*, **227**,  
910 115331.

911 Mulder, I., Siemens, J., Sentek, V., Amelung, W., Smalla, K., Jechalke, S. 2018. Quaternary ammonium  
912 compounds in soil: implications for antibiotic resistance development. *Reviews in*  
913 *Environmental Science and Bio/Technology*, **17**(1), 159-185.

914 Murray, C.J.L., Ikuta, K.S., Sharara, F., Swetschinski, L., Aguilar, G.R., Gray, A., Han, C., Bisignano,  
915 C., Rao, P., Wool, E., Johnson, S.C., Browne, A.J., Chipeta, M.G., Fell, F., Hackett, S., Haines-  
916 Woodhouse, G., Hamadani, B.H.K., Kumaran, E.A.P., McManigal, B., Agarwal, R., Akech, S.,  
917 Albertson, S., Amuasi, J., Andrews, J., Aravkin, A., Ashley, E., Bailey, F., Baker, S., Basnyat,  
918 B., Bekker, A., Bender, R., Bethou, A., Bielicki, J., Boonkasidecha, S., Bukosia, J., Carvalho,  
919 C., Castaneda-Orjuela, C., Chansamouth, V., Chaurasia, S., Chiurchiu, S., Chowdhury, F., Cook,  
920 A.J., Cooper, B., Cressey, T.R., Criollo-Mora, E., Cunningham, M., Darboe, S., Day, N.P.J., De  
921 Luca, M., Dokova, K., Dramowski, A., Dunachie, S.J., Eckmanns, T., Eibach, D., Emami, A.,  
922 Feasey, N., Fisher-Pearson, N., Forrest, K., Garrett, D., Gastmeier, P., Giref, A.Z., Greer, R.C.,  
923 Gupta, V., Haller, S., Haselbeck, A., Hay, S.I., Holm, M., Hopkins, S., Iregebu, K.C., Jacobs, J.,  
924 Jarovsky, D., Javanmardi, F., Khorana, M., Kissoon, N., Kobeissi, E., Kostyanov, T., Krapp, F.,

925 Krumkamp, R., Kumar, A., Kyu, H.H., Lim, C., Limmathurotsakul, D., Loftus, M.J., Lunn, M.,  
926 Ma, J., Mturi, N., Munera-Huertas, T., Musicha, P., Mussi-Pinhata, M.M., Nakamura, T.,  
927 Nanavati, R., Nangia, S., Newton, P., Ngoun, C., Novotney, A., Nwakanma, D., Obiero, C.W.,  
928 Olivás-Martínez, A., Olliaro, P., Ooko, E., et al. 2022. Global burden of bacterial antimicrobial  
929 resistance in 2019: A systematic analysis. *Lancet*, **399**(10325), 629-655.

930 Nadimpalli, M.L., Chan, C.W., Doron, S. 2021. Antibiotic resistance: a call to action to prevent the next  
931 epidemic of inequality. *Nature Medicine*, **27**(2), 187-188.

932 Ostermann, A., Gao, J., Welp, G., Siemens, J., Roelcke, M., Heimann, L., Nieder, R., Xue, Q., Lin, X.,  
933 Sandhage-Hofmann, A., Amelung, W. 2014. Identification of soil contamination hotspots with  
934 veterinary antibiotics using heavy metal concentrations and leaching data—a field study in  
935 China. *Environmental Monitoring and Assessment*, **186**(11), 7693-7707.

936 Pärnänen, K.M.M., Narciso-da-Rocha, C., Kneis, D., Berendonk Thomas, U., Cacace, D., Do Thi, T.,  
937 Elpers, C., Fatta-Kassinos, D., Henriques, I., Jaeger, T., Karkman, A., Martinez Jose, L., Michael  
938 Stella, G., Michael-Kordatou, I., O’Sullivan, K., Rodriguez-Mozaz, S., Schwartz, T., Sheng, H.,  
939 Sørum, H., Stedtfeld Robert, D., Tiedje James, M., Giustina Saulo Varela, D., Walsh, F., Vaz-  
940 Moreira, I., Virta, M., Manaia Célia, M. 2019. Antibiotic resistance in European wastewater  
941 treatment plants mirrors the pattern of clinical antibiotic resistance prevalence. *Science*  
942 *Advances*, **5**(3), eaau9124.

943 Partridge, S.R., Kwong, S.M., Firth, N., Jensen, S.O. 2018. Mobile genetic elements associated with  
944 antimicrobial resistance. *Clinical Microbiology Reviews*, **31**(4), e00088-17.

945 Patangia, D.V., Ryan, C.A., Dempsey, E., Stanton, C., Ross, R.P. 2022. Vertical transfer of antibiotics  
946 and antibiotic resistant strains across the mother/baby axis. *Trends in Microbiology*, **30**(1), 47-  
947 56.

948 Pérez-Valera, E., Kyselková, M., Ahmed, E., Sladeczek, F.X.J., Goberna, M., Elhottová, D. 2019. Native  
949 soil microorganisms hinder the soil enrichment with antibiotic resistance genes following  
950 manure applications. *Scientific Reports*, **9**(1), 6760.

951 Pitié, M., Pratviel, G. 2010. Activation of DNA carbon–hydrogen bonds by metal complexes. *Chemical*  
952 *Reviews*, **110**(2), 1018-1059.

953 Rochegüe, T., Haenni, M., Mondot, S., Astruc, C., Cazeau, G., Ferry, T., Madec, J.-Y., Lupo, A. 2021.  
954 Impact of antibiotic therapies on resistance genes dynamic and composition of the animal gut  
955 microbiota. *Animals*, **11**(11), 3280.

956 Rodríguez-Beltrán, J., DelaFuente, J., Leon-Sampedro, R., MacLean, R.C., San Millán, A. 2021. Beyond  
957 horizontal gene transfer: the role of plasmids in bacterial evolution. *Nature Reviews*  
958 *Microbiology*, **19**(6), 347-359.

959 Saha, D., Visconti, M.C., Desipio, M.M., Thorpe, R. 2020. Inactivation of antibiotic resistance gene by  
960 ternary nanocomposites of carbon nitride, reduced graphene oxide and iron oxide under visible  
961 light. *Chemical Engineering Journal*, **382**, 122857.

962 Seiler, C., Berendonk, T. 2012. Heavy metal driven co-selection of antibiotic resistance in soil and water  
963 bodies impacted by agriculture and aquaculture. *Frontiers in Microbiology*, **3**, 399.

964 Shan, G., Li, W., Gao, Y., Tan, W., Xi, B. 2021. Additives for reducing nitrogen loss during composting:  
965 A review. *Journal of Cleaner Production*, **307**, 127308.

966 Shao, B., Liu, Z., Tang, L., Liu, Y., Liang, Q., Wu, T., Pan, Y., Zhang, X., Tan, X., Yu, J. 2022. The effects  
967 of biochar on antibiotic resistance genes (ARGs) removal during different environmental  
968 governance processes: A review. *Journal of Hazardous Materials*, **435**, 129067.

- 969 Sharma, V.K., Yngard, R.A., Lin, Y. 2009. Silver nanoparticles: Green synthesis and their antimicrobial  
970 activities. *Advances in Colloid and Interface Science*, **145**(1), 83-96.
- 971 Singh, K.S., Anand, S., Dholpuria, S., Sharma, J.K., Blankenfeldt, W., Shouche, Y. 2021. Antimicrobial  
972 resistance dynamics and the one-health strategy: A review. *Environmental Chemistry Letters*,  
973 **19**(4), 2995-3007.
- 974 Smith, S.C., Rodrigues, D.F. 2015. Carbon-based nanomaterials for removal of chemical and biological  
975 contaminants from water: A review of mechanisms and applications. *Carbon*, **91**, 122-143.
- 976 Soler, N., Forterre, P. 2020. Vesiduction: the fourth way of HGT. *Environmental Microbiology*, **22**(7),  
977 2457-2460.
- 978 Sridhar, S., Turbett, S.E., Harris, J.B., LaRocque, R.C. 2021. Antimicrobial-resistant bacteria in  
979 international travelers. *Current Opinion in Infectious Diseases*, **34**(5), 423-431.
- 980 Su, H.-C., Liu, Y.-S., Pan, C.-G., Chen, J., He, L.-Y., Ying, G.-G. 2018. Persistence of antibiotic  
981 resistance genes and bacterial community changes in drinking water treatment system: From  
982 drinking water source to tap water. *Science of The Total Environment*, **616-617**, 453-461.
- 983 Sun, M., Ye, M., Zhang, Z., Zhang, S., Zhao, Y., Deng, S., Kong, L., Ying, R., Xia, B., Jiao, W., Cheng,  
984 J., Feng, Y., Liu, M., Hu, F. 2019. Biochar combined with polyvalent phage therapy to mitigate  
985 antibiotic resistance pathogenic bacteria vertical transfer risk in an undisturbed soil column  
986 system. *Journal of Hazardous Materials*, **365**, 1-8.
- 987 Tan, Y., Wen, Q., Li, M., Yang, B., Tang, Y., Li, A., Chen, Z. 2022. Simultaneous antibiotic resistance  
988 genes reduction and membrane fouling mitigation by a hybrid process of magnetic activated  
989 carbon adsorption and ultrafiltration for wastewater reuse. *Separation and Purification  
990 Technology*, **303**, 122227.
- 991 Tiedje, J.M., Wang, F., Manaia, C.M., Virta, M., Sheng, H., Ma, L., Zhang, T., Topp, E. 2019. Antibiotic  
992 resistance genes in the human-impacted environment: A One Health perspective. *Pedosphere*,  
993 **29**(3), 273-282.
- 994 Tyers, M., Wright, G.D. 2019. Drug combinations: a strategy to extend the life of antibiotics in the 21st  
995 century. *Nature Reviews Microbiology*, **17**(3), 141-155.
- 996 UNEP, U.E.P. 2022. Antimicrobial resistance: a global threat. *Environmental Dimensions of  
997 Antimicrobial Resistance*,  
998 [https://wedocs.unep.org/bitstream/handle/20.500.11822/38373/antimicrobial\\_R.pdf](https://wedocs.unep.org/bitstream/handle/20.500.11822/38373/antimicrobial_R.pdf).
- 999 Van Boeckel Thomas, P., Pires, J., Silvester, R., Zhao, C., Song, J., Criscuolo Nicola, G., Gilbert, M.,  
1000 Bonhoeffer, S., Laxminarayan, R. 2019. Global trends in antimicrobial resistance in animals in  
1001 low- and middle-income countries. *Science*, **365**(6459), eaaw1944.
- 1002 Wang, F., Fu, Y., Sheng, H., Topp, E., Jiang, X., Zhu, Y., Tiedje, J.M. 2021. Antibiotic resistance in the  
1003 soil ecosystem: A One Health perspective. *Current Opinion in Environmental Science & Health*,  
1004 **20**, 100230.
- 1005 Wang, F., Xu, M., Stedtfeld, R.D., Sheng, H., Fan, J., Liu, M., Chai, B., de Carvalho, T.S., Li, H., Li, Z.,  
1006 Hashsham, S.A., Tiedje, J.M. 2018. Long-term effect of different fertilization and cropping  
1007 systems on the soil antibiotic resistome. *Environmental Science & Technology*, **52**(22), 13037-  
1008 13046.
- 1009 Wang, J., Chen, B. 2015. Adsorption and coadsorption of organic pollutants and a heavy metal by  
1010 graphene oxide and reduced graphene materials. *Chemical Engineering Journal*, **281**, 379-388.
- 1011 Wang, M., Liu, H., Dai, X. 2020. Dosage effects of lincomycin mycelial residues on lincomycin  
1012 resistance genes and soil microbial communities. *Environmental Pollution*, **256**, 113392.

- 1013 Wang, M., Wang, Y., Ni, X., Hou, X., Ma, D., Li, Q., Gao, B. 2022. How multi-walled carbon nanotubes  
1014 in wastewater influence the fate of coexisting antibiotic resistant genes in the subsequent  
1015 disinfection process. *Chemosphere*, **302**, 134641.
- 1016 Wang, Y., Ni, X., Hou, X., Ma, D., Zhang, B., Li, Q., Gao, B. 2023. The inactivation of antibiotic-resistant  
1017 bacteria and the damage of antibiotic-resistant genes using an electrified carbon nanotube  
1018 membrane-NaClO system. *Chemical Engineering Journal*, **454**, 140183.
- 1019 Waseem, H., Williams, M.R., Stedtfeld, R.D., Hashsham, S.A. 2017. Antimicrobial resistance in the  
1020 environment. *Water environment research : a research publication of the Water Environment  
1021 Federation*, **89**(10), 921-941.
- 1022 Winter, M., Buckling, A., Harms, K., Johnsen, P.J., Vos, M. 2021. Antimicrobial resistance acquisition  
1023 via natural transformation: context is everything. *Current Opinion in Microbiology*, **64**, 133-  
1024 138.
- 1025 Wu, C., Fu, L., Li, H., Liu, X., Wan, C. 2022. Using biochar to strengthen the removal of antibiotic  
1026 resistance genes: Performance and mechanism. *Science of The Total Environment*, **816**, 151554.
- 1027 Wu, J., Wu, C., Zhou, C., Dong, L., Liu, B., Xing, D., Yang, S., Fan, J., Feng, L., Cao, G., You, S. 2020.  
1028 Fate and removal of antibiotic resistance genes in heavy metals and dye co-contaminated  
1029 wastewater treatment system amended with  $\beta$ -cyclodextrin functionalized biochar. *Science of  
1030 The Total Environment*, **723**, 137991.
- 1031 Wu, M., Kempaiah, R., Huang, P.-J.J., Maheshwari, V., Liu, J. 2011. Adsorption and desorption of DNA  
1032 on graphene oxide studied by fluorescently labeled oligonucleotides. *Langmuir*, **27**(6), 2731-  
1033 2738.
- 1034 Wu, S., Wu, Y., Huang, Q., Cai, P. 2021. Insights into conjugative transfer of antibiotic resistance genes  
1035 affected by soil minerals. *European Journal of Soil Science*, **72**(3), 1143-1153.
- 1036 Xiang, Y., Xu, Z., Wei, Y., Zhou, Y., Yang, X., Yang, Y., Yang, J., Zhang, J., Luo, L., Zhou, Z. 2019.  
1037 Carbon-based materials as adsorbent for antibiotics removal: Mechanisms and influencing  
1038 factors. *Journal of Environmental Management*, **237**, 128-138.
- 1039 Xiao, R., Awasthi, M.K., Li, R., Park, J., Pensky, S.M., Wang, Q., Wang, J.J., Zhang, Z. 2017. Recent  
1040 developments in biochar utilization as an additive in organic solid waste composting: A review.  
1041 *Bioresource Technology*, **246**, 203-213.
- 1042 Xie, J., Gu, J., Wang, X., Hu, T., Sun, W., Lei, L., Zhang, R., Guo, H. 2021. Insights into the beneficial  
1043 effects of woody peat for reducing abundances of antibiotic resistance genes during composting.  
1044 *Bioresource Technology*, **342**, 125903.
- 1045 Xie, J., Jin, L., He, T., Chen, B., Luo, X., Feng, B., Huang, W., Li, J., Fu, P., Li, X. 2019. Bacteria and  
1046 antibiotic resistance genes (ARGs) in PM<sub>2.5</sub> from China: Implications for human exposure.  
1047 *Environmental Science & Technology*, **53**(2), 963-972.
- 1048 Xie, W., Wang, Y., Yuan, J., Hong, W., Niu, G., Zou, X., Yang, X., Shen, Q., Zhao, F. 2022. Prevalent  
1049 and highly mobile antibiotic resistance genes in commercial organic fertilizers. *Environment  
1050 International*, **162**, 107157.
- 1051 Xin, Q., Shah, H., Nawaz, A., Xie, W., Akram, M.Z., Batool, A., Tian, L., Jan, S.U., Boddula, R., Guo,  
1052 B., Liu, Q., Gong, J.R. 2019. Antibacterial carbon-based nanomaterials. *Advanced Materials*,  
1053 **31**(45), 1804838.
- 1054 Xu, L., Zhao, J., Liu, Z., Wang, Z., Yu, K., Xing, B. 2019. Cleavage and transformation inhibition of  
1055 extracellular antibiotic resistance genes by graphene oxides with different lateral sizes. *Science  
1056 of The Total Environment*, **695**, 133932.

- 1057 Ye, M., Sun, M., Feng, Y., Wan, J., Xie, S., Tian, D., Zhao, Y., Wu, J., Hu, F., Li, H., Jiang, X. 2016.  
1058 Effect of biochar amendment on the control of soil sulfonamides, antibiotic-resistant bacteria,  
1059 and gene enrichment in lettuce tissues. *Journal of Hazardous Materials*, **309**, 219-227.
- 1060 Ye, S., Xu, Y., Huang, L., Lai, W., Deng, L., Lin, Z., Peng, H., Zhou, X., Xie, G. 2021. MWCNT/BiVO<sub>4</sub>  
1061 photocatalyst for inactivation performance and mechanism of *Shigella flexneri* HL, antibiotic-  
1062 resistant pathogen. *Chemical Engineering Journal*, **424**, 130415.
- 1063 Yousefi, M., Dadashpour, M., Hejazi, M., Hasanzadeh, M., Behnam, B., de la Guardia, M., Shadjou, N.,  
1064 Mokhtarzadeh, A. 2017. Anti-bacterial activity of graphene oxide as a new weapon  
1065 nanomaterial to combat multidrug-resistance bacteria. *Materials Science & Engineering C-  
1066 Materials for Biological Applications*, **74**, 568-581.
- 1067 Yu, D., Xu, Z., Pedrycz, W., Wang, W. 2017a. Information sciences 1968–2016: A retrospective analysis  
1068 with text mining and bibliometric. *Information Sciences*, **418-419**, 619-634.
- 1069 Yu, W., Zhan, S., Shen, Z., Zhou, Q. 2018. A newly synthesized Au/GO-Co<sub>3</sub>O<sub>4</sub> composite effectively  
1070 inhibits the replication of tetracycline resistance gene in water. *Chemical Engineering Journal*,  
1071 **345**, 462-470.
- 1072 Yu, W., Zhan, S., Shen, Z., Zhou, Q., Yang, D. 2017b. Efficient removal mechanism for antibiotic  
1073 resistance genes from aquatic environments by graphene oxide nanosheet. *Chemical  
1074 Engineering Journal*, **313**, 836-846.
- 1075 Zha, Y., Li, Z., Zhong, Z., Ruan, Y., Sun, L., Zuo, F., Li, L., Hou, S. 2022. Size-dependent enhancement  
1076 on conjugative transfer of antibiotic resistance genes by micro/nanoplastics. *Journal of  
1077 Hazardous Materials*, **431**, 128561.
- 1078 Zhan, H., Wang, Y., Mi, X., Zhou, Z., Wang, P., Zhou, Q. 2020. Effect of graphitic carbon nitride powders  
1079 on adsorption removal of antibiotic resistance genes from water. *Chinese Chemical Letters*,  
1080 **31**(10), 2843-2848.
- 1081 Zhang, L., Gu, J., Wang, X., Sun, W., Yin, Y., Sun, Y., Guo, A., Tuo, X. 2017. Behavior of antibiotic  
1082 resistance genes during co-composting of swine manure with Chinese medicinal herbal residues.  
1083 *Bioresource Technology*, **244**, 252-260.
- 1084 Zhang, X., Gong, Z., Allinson, G., Li, X., Jia, C. 2022. Joint effects of bacterium and biochar in  
1085 remediation of antibiotic-heavy metal contaminated soil and responses of resistance gene and  
1086 microbial community. *Chemosphere*, **299**, 134333.
- 1087 Zhang, Y., Li, H., Gu, J., Qian, X., Yin, Y., Li, Y., Zhang, R., Wang, X. 2016. Effects of adding different  
1088 surfactants on antibiotic resistance genes and intI1 during chicken manure composting.  
1089 *Bioresource Technology*, **219**, 545-551.
- 1090 Zhao, H., Wei, L., Li, H., Zhang, M., Cao, B., Bian, J., Zhan, S. 2021. Appropriateness of antibiotic  
1091 prescriptions in ambulatory care in China: a nationwide descriptive database study. *The Lancet  
1092 Infectious Diseases*, **21**(6), 847-857.
- 1093 Zheng, H., Feng, N., Yang, T., Shi, M., Wang, X., Zhang, Q., Zhao, J., Li, F., Sun, K., Xing, B. 2021.  
1094 Individual and combined applications of biochar and pyroligneous acid mitigate dissemination  
1095 of antibiotic resistance genes in agricultural soil. *Science of The Total Environment*, **796**, 148962.
- 1096 Zhou, Z., Shen, Z., Cheng, Z., Zhang, G., Li, M., Li, Y., Zhan, S., Crittenden, J.C. 2020. Mechanistic  
1097 insights for efficient inactivation of antibiotic resistance genes: a synergistic interfacial  
1098 adsorption and photocatalytic-oxidation process. *Science Bulletin*, **65**(24), 2107-2119.
- 1099 Zhu, D., Ding, J., Wang, Y.-F., Zhu, Y.-G. 2022. Effects of trophic level and land use on the variation of  
1100 animal antibiotic resistome in the soil food web. *Environmental Science & Technology*, **56**(21),

1101 14937-14947.

1102 Zhu, Y., Gillings, M., Simonet, P., Stekel, D., Banwart, S., Penuelas, J. 2017. Microbial mass movements.

1103 *Science*, **357**(6356), 1099-1100.

1104 Zhu, Y., Johnson, T.A., Su, J., Qiao, M., Guo, G., Stedtfeld, R.D., Hashsham, S.A., Tiedje, J.M. 2013.

1105 Diverse and abundant antibiotic resistance genes in Chinese swine farms. *Proceedings of the*

1106 *National Academy of Sciences of the United States of America*, **110**(9), 3435-3440.

1107 Zhu, Y., Zhao, Y., Zhu, D., Gillings, M., Penuelas, J., Ok, Y.S., Capon, A., Banwart, S. 2019. Soil biota,

1108 antimicrobial resistance and planetary health. *Environment International*, **131**, 105059.

1109 Zou, H., He, L., Gao, F., Zhang, M., Chen, S., Wu, D., Liu, Y., He, L., Bai, H., Ying, G. 2021. Antibiotic

1110 resistance genes in surface water and groundwater from mining affected environments. *Science*

1111 *of The Total Environment*, **772**, 145516.

1112 Zou, W., Li, X., Lai, Z., Zhang, X., Hu, X., Zhou, Q. 2016. Graphene oxide inhibits antibiotic uptake and

1113 antibiotic resistance gene propagation. *ACS Applied Materials & Interfaces*, **8**(48), 33165-

1114 33174.

1115

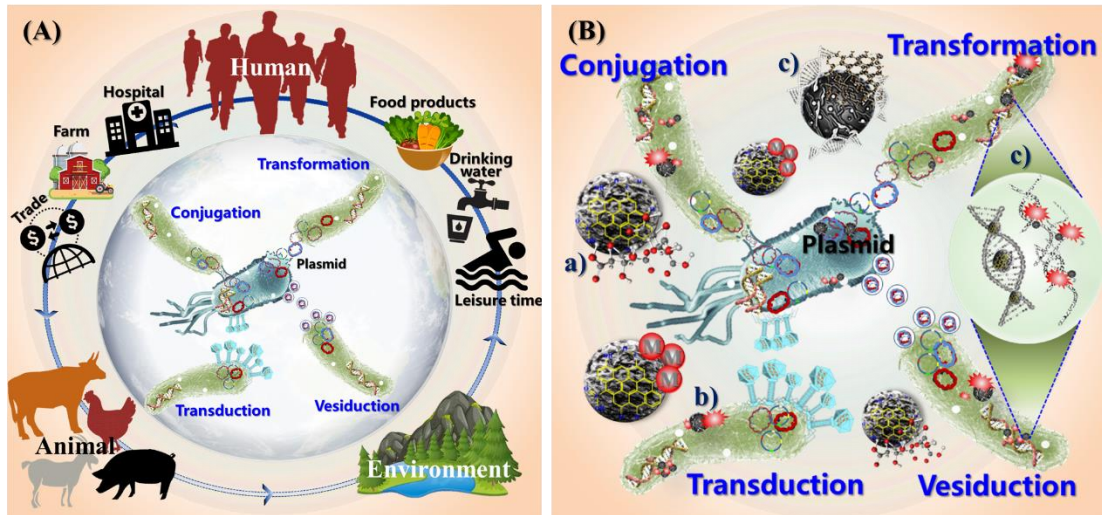


Fig. 1 (A) General routes of horizontal gene transfer (HGT) within natural communities including conjugation, transformation, transduction and vesiduction, and the global transmission of antimicrobial resistance among the human-impacted environments within a One-Health pathway. (B) The feasibility using carbon-based materials to combat antibiotic resistance, including a) reducing the selection pressure imposed by the environmental pollutants (e.g., organic pollutants and heavy metals) on HGT, b) inhibiting the cellular activity and integrity of donor bacteria and recipient bacteria by oxidative damage and physical penetration etc. in HGT processes, c) adsorbing or fragmenting the free DNA encoding antibiotic resistance genes in HGT processes.

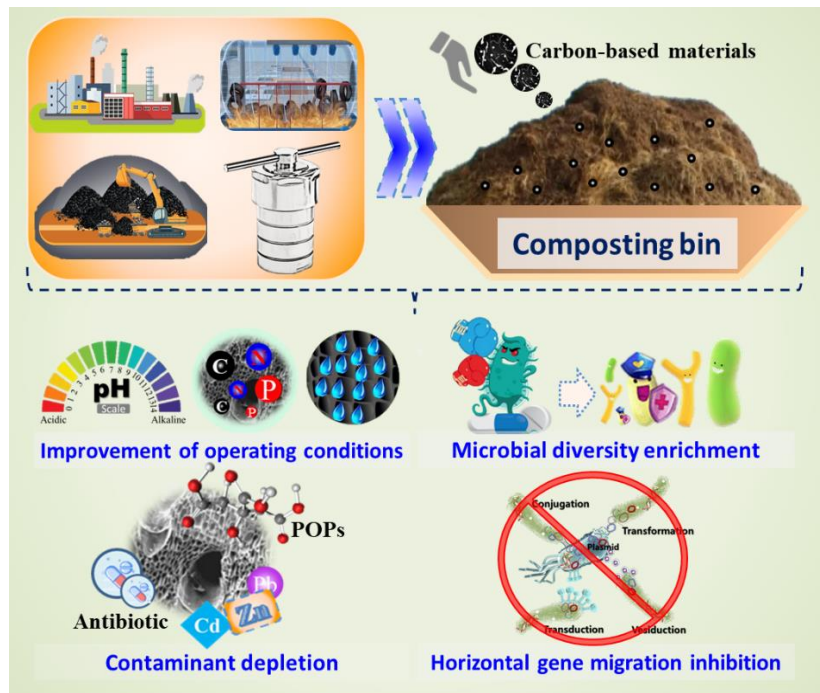


Fig. 2 The underlying mechanisms of antibiotic resistance gene (ARG) alleviation via the application of carbon-based additives in the composting. POPs, persistent organic pollutants.

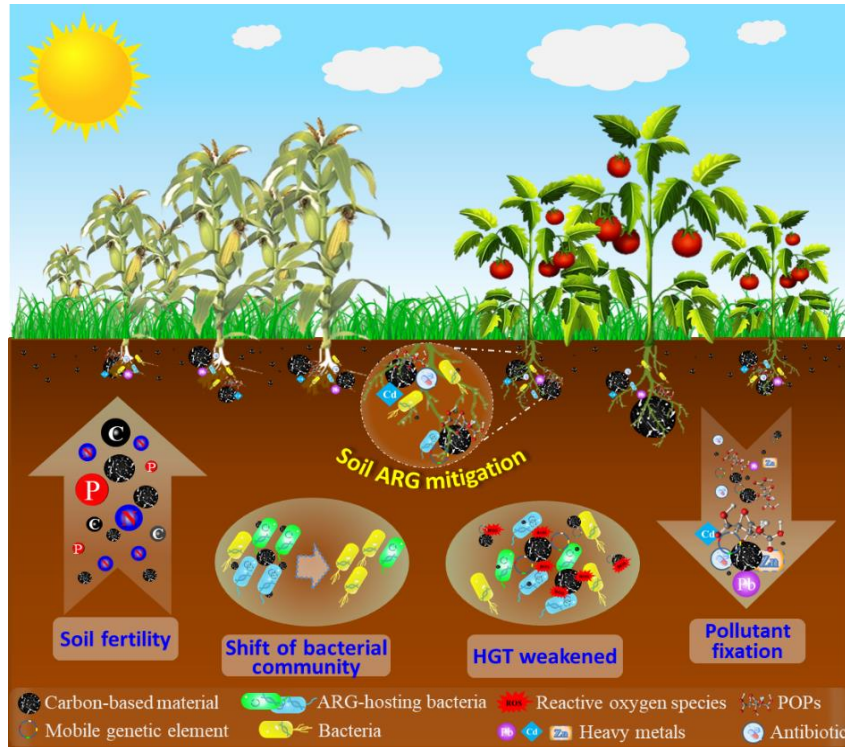


Fig. 3 The underlying mechanisms of antibiotic resistance gene (ARG) alleviation in the soil amended with carbon-based materials. POPs, persistent organic pollutants; HGT, horizontal gene transfer.

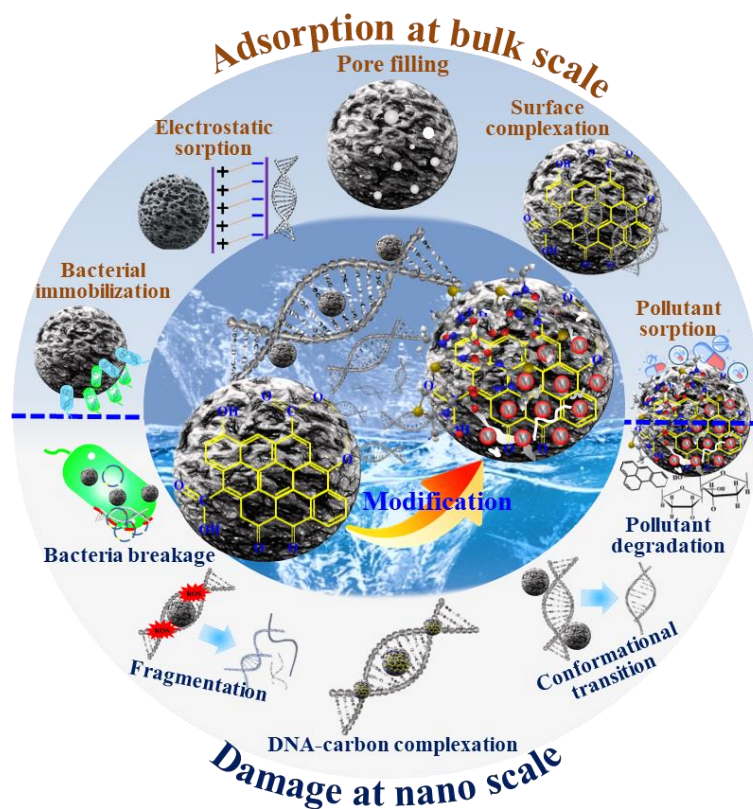


Fig. 4 The potential mechanisms of antibiotic resistance gene (ARG) alleviation using carbon-based materials in aquatic environments.

Table 1 Factors influence the removal of antibiotic resistance genes using graphene oxide in water environment.

Category	Influence factors	Conditions	Types	Results	Mechanisms	Ref.
Graphene oxide	Lateral size	0.08 $\mu\text{m}^2$ 0.17 $\mu\text{m}^2$ 0.60 $\mu\text{m}^2$	Kanamycin resistance gene - containing plasmid DNA	The amplification and transformation of <i>aphA</i> gene were both inhibited.	Graphene oxide could intercalate into plasmid DNA base pairs, thus resulting in structural damage and the inhibition was stronger with smaller lateral sizes.	(Xu et al., 2019)
		1.0 $\mu\text{m}^2$				
Graphene oxide	Concentration	0.1 mg/L 1 mg/L 10 mg/L 50 mg/L 80 mg/L	<i>E. coli</i> HB101 and NK5449, tetracycline resistance gene and kanamycin resistance gene	(1) Graphene oxide had a limited effect on antibiotic-resistant bacteria inactivation; (2) Graphene oxide can promote the conjugative transfer of ARGs but the promotion rate varied according to the concentrations.	Graphene oxide with high concentrations have obvious bacteriostatic abilities via the generated oxidative stress and lead to an increase of cell membrane permeability, and promote the conjugative transfer.	(Guo & Zhang, 2017)
		100 mg/L				
DNA	DNA length	12-mer 18-mer 24-mer 36-mer	Single-stranded DNA	Short DNAs are adsorbed more rapidly and bind	Shorter DNA binds to the surface with faster kinetics	(Wu et al., 2011)

Category	Influence factors	Conditions	Types	Results	Mechanisms	Ref.
				more tightly to the surface of graphene oxide nanosheet than long ones.	and higher adsorption efficiency.	
		cyclic (c) - stranded- ARGs			The ds-ARGs exposed a higher number of available binding groups and these anionic charged groups located all along the linear double-stranded molecules and established a multi-loci contact with graphene oxide, whereas most of the phosphate groups of c-ARGs localized within the supercoiled molecule cannot influence adsorption.	(Yu et al., 2017b)
	DNA structures	double-stranded (ds)-ARGs	DNA strands	Graphene oxide nanosheet had better removal performance not only for ds-ARGs but also for c-ARGs, but showed distinct adsorption kinetics.		

Category	Influence factors	Conditions	Types	Results	Mechanisms	Ref.
Environmental factors	Gene type	Different base compositions	16S rRNA, <i>sulI</i> , <i>sulII</i> and <i>intI</i> genes	Graphene oxide has significant effects on the absolute abundance of <i>intI</i> and <i>sulI</i> genes but have no significant effects on the absolute abundance of 16S rRNA and <i>sulII</i> genes.	(1) Graphene oxide (< 1 mg/L) has limited influence on the microbial viability; (2) Reactive groups in the combination of graphene oxide and DNA may vary towards different base compositions of different genes.	(Zou et al., 2016)
				Acetate buffer (pH 5.0 and 6.0) Tris-HCl (pH 7.0 and 8.0)	<i>TetA</i> , <i>sul2</i> , <i>ermB</i> and <i>ampC</i> genes	Acidic or neutral condition (from 5.0 to 7.0) was more beneficial to remove ARGs than alkaline condition (pH at 8.0-9.0).
	Electrolyte	Na <sup>+</sup>  Mg <sup>2+</sup>	<i>TetA</i> , <i>sul2</i> , <i>ermB</i> and <i>ampC</i> genes	With the presence of Na <sup>+</sup> , the removal efficiency was higher than 75% for c-ARGs and was close to 100% for ds-ARGs.	(1) The electrostatic repulsion between graphene oxide and ARGs can be greatly offset by cation ions, which act as salt bridges	(Pitié & Pratviel, 2010; Yu et al., 2017b)
				Carbonate buffer (pH 9.0)		

Category	Influence factors	Conditions	Types	Results	Mechanisms	Ref.
				Comparative removal capacity of graphene oxide for ARGs was enhanced more significantly by Mg <sup>2+</sup> than Na <sup>+</sup> .	and bring the ARGs close to the graphene oxide surface for binding; (2) Larger fractional surface densities in divalent cation than in monovalent cation allow divalent metal ions more effective in screening charges and acting as a bridge; (3) Some divalent transition metal ions can be chelated and then transferred by graphene oxide between DNA base pairs to promote the inhibition of horizontal gene transfer.	
		Cu <sup>2+</sup>	DNA strands	Graphene oxide/Cu <sup>2+</sup> sheets were inserted into DNA, and Cu <sup>2+</sup> ions could be assigned between DNA base pairs or into the DNA backbone, which could lead to the unfolding of DNA.		
	Temperature	4 °C 20 °C 30 °C	<i>TetA</i> , <i>sul2</i> , <i>ermB</i> and <i>ampC</i> genes	The removal rate of <i>tetA</i> , <i>sul2</i> , <i>ermB</i> and <i>ampC</i> genes increases along with	The adsorption of ARGs on graphene oxide was spontaneous and	(Yu et al., 2017b)

Category	Influence factors	Conditions	Types	Results	Mechanisms	Ref.
				the increase temperature from 4 °C to 20 °C, followed by a decrease tendency when temperature increases from 20 °C to 30 °C.	endothermic, while mechanisms about the adsorption of graphene oxide to ARGs fluctuating with the temperature are elusive.	