人工合成纳米颗粒在水生食物链中的分布、传递及其影响因素

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摘要 纳米技术作为一种最具有市场应用潜力的新兴科学技术, 近十年来在基础理论和应用研究等方面迅猛发展, 使其在化工、医疗、电子、能源、环境保护等行业得到了广泛的应用. 人工合成纳米颗粒(engineered nanoparticles, ENPs)在纳米产品的整个生命周期中将不可避免地进入水环境, 与水生生物直接或间接(营养传递)的接触, 从而沿水生食物链进行传递和转移, 并影响生物的一系列生命活动. 本文以不同水生生物为对象, 总结了ENPs在不同类群的生物中的分布特点, 着重探讨了ENPs在淡水和海洋食物链中的传递规律, 并分析了ENPs性质和水环境因素对传递过程的影响. 本文最后对ENPs在水生食物链中的研究现状、前景和面临的挑战进行了分析和展望.

关键词 人工合成纳米颗粒, 生物分布, 水生食物链, 营养传递, 生物放大

纳米颗粒(nanoparticles, NPs)是指在三维空间中至少有一维处于纳米尺度范围(1~100 nm)的材料. 根据其来源的差异可分为天然纳米颗粒(natural nanoparticles)和人工合成纳米颗粒(engineered nanoparticles, ENPs). 随着纳米技术的日益革新, ENPs越来越多地应用于高效催化剂、生物传感器、药物载体、吸附剂、海水淡化等方面^[1~5]. 水环境是地球上物质循环和能量流动的大本营, 是各种污染物重要的“汇”. ENPs在纳米产品的生产、消费和废弃过程中必然会通过人类有意或无意的行为释放到水环境中, 发生溶解、团聚、沉降、再悬浮等一系列的物理化学行为^[6], 对水生生物甚至水生食物链造成严重威胁, 从而对水体环境造成冲击. 不同种类的ENPs的水环境行为具有特异性, 并且不同种类的水生生物因自身的生

活习性、调节能力等的差异对ENPs的敏感性也不尽相同, 从而造成ENPs在水生生物体内分布的差异性. 另外, 水环境中不同的水生生物因捕食与被捕食关系构成了水生食物链或者食物网, 那么进入低营养级生物体内的ENPs就会随着食物链传递到高营养级, 从而造成ENPs沿食物链或者食物网的传递^[6]. 食物链中被捕食者生物体内的分布情况, 势必会影响高营养级中的分布以及传递过程^[7]. 因此, 研究ENPs沿水生食物链的传递规律是非常必要的. 本文首先归纳了ENPs在不同水生生物中的分布规律, 并且从水介质差异角度出发, 着重探讨了ENPs在淡水和海水中沿水生食物链传递机制, 水环境因素和ENPs自身性质对传递过程的影响, 最后从多个角度对纳米毒理学在水生食物链中的研究现状、前景和面临的挑

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战进行了分析和展望。

1 ENPs在水生生物体中的分布

ENPs进入水生环境中会与不同种类的水生生物发生不同的相互作用,进而使得其在生物体的分布呈现不同的结局,本文从4种典型水生生物入手,深入阐述ENPs的摄取和分布规律。

1.1 ENPs-微生物

微生物作为环境中的分解者,同时也是无脊椎动物或者原生动物的食物。由于细胞壁的存在,ENPs会吸附在微生物细胞壁表面,使细胞壁成为阻碍ENPs内化的第一道屏障(图1,过程①);另外由于微生物能够分泌大量的胞外聚合物(extracellular polymer substances, EPS),使得ENPs被络合吸附在EPS表面,减少ENPs的进入^[8,9](图1,过程②);小尺寸的ENPs及金属ENPs释放出来的离子可以通过细胞壁间隙以及细胞膜上的离子通道进入细胞(图1,过程③)。当ENPs的尺寸在10 nm~5 μm 时,可通过内吞作用被

内化(图1,过程④)^[10,11]。一些金属ENPs^[12]和具有切割效应的碳材料^[13]则可以通过细胞壁和细胞膜的损伤进入到细胞(图1,过程⑤)等。ENPs进入细胞后,会与细胞质基质、细胞器^[14,15](如叶绿体、线粒体)以及遗传物质(细胞核或者拟核)^[16,17]相互作用(图1)。ENPs一旦进入细胞或者细胞核,就有可能造成胞液泄漏,破坏遗传物质^[9],对于子代乃至所处食物链(网)产生不可控的后果。而对于一些没有细胞壁结构的生物,ENPs也会吸附在细胞膜表面,与蛋白质形成“电晕”阻碍其进入细胞^[18](图1,过程⑥)。此外,跨膜运输和内吞作用也是ENPs进入这类细胞的主要途径。

1.2 ENPs-水生植物

水生植物与陆生植物相比角质层较薄更柔软、茎和叶上的空隙更多,从而为ENPs进入生物体内提供了更多的位点。而植物叶片上不同程度的蜡质层,导致ENPs在叶片上的吸附存在差异。蜡质层厚的叶片更容易吸附亲脂性的ENPs,例如 C_{60} 通过氢键与金鱼的纤维素紧密结合,形成不可逆的吸附^[19]。对于

图1 ENPs在细胞上的分布

Figure 1 The distribution of ENPs on the cell

沉水植物,如狐尾藻(*Myriophyllum simulans*)、蜈蚣草(*Egeria densa*), ENPs能够进入到根、茎、叶中^[20],这主要是由于沉水植物与水中的ENPs能够充分接触;对于浮水植物,如槐叶萍(*Salvinia natans*)、水葫芦(*Eichhornia crassipes*), ENPs与根、水中茎接触,进而进入水生植物体内,并且能够通过沉水叶片的气孔进入植物体内^[21,22];对于挺水植物来说,如水葱(*Schoenoplectus tabernaemontani*)^[23], ENPs首先蓄积在根部.一旦ENPs进入植物体内,就会在植物体内发生迁移,到达植物的嫩枝、叶肉等组织中^[24],经食物链传递进入高营养级体内.由于高等植物的细胞壁具有半渗透性,可以允许10~50 nm的粒子自由通过^[25],而气孔为5~20 nm,当ENPs的尺寸小于气孔时,就可以穿过气孔,进入细胞,高等水生植物也会通过植物细胞的内吞作用将ENPs内化^[21].

1.3 ENPs-水生无脊椎动物

水生无脊椎动物一般以藻类为食,并且被鱼类等大型动物捕食,在水生食物链中起着至关重要的作用.无脊椎动物,如蚌类(*Mytilus galloprovincialis*)^[26]、牡蛎(*Crassostrea virginica*)^[27]、扇贝(*Chlamys islandica*)^[28]等,能够分泌有机-无机的黏液^[29],使ENPs通过吸附作用吸附在生物的外表皮或者刚毛上^[30].由于这些生物滤食性的摄食方式, ENPs主要分布于其外套膜以及鳃和消化腺内.对于一些较高级、运动敏捷、头部发达的无脊椎动物,其分化明显,生有触角和眼等感觉器官,如大型蚤(*Daphnia magna*)^[31]、蜗牛

(*Austropeplea ollula*, *Biomphalaria straminea*)^[32]、田螺(*Lymnaea stagnalis*)^[33]、小龙虾(*Orconectes virilis*, *Procambarus clarkii*)^[34]等, ENPs主要分布在鳃、肝胰腺以及肠道上.另外同种生物的不同物种对同一种ENPs的摄食也存在差异,这主要取决于生物对ENPs的生物敏感性.不容忽视的是ENPs可以进入无脊椎动物的血液中,并且可以在淋巴细胞和血细胞以及消化系统中循环^[35]. ENPs进入无脊椎动物细胞中的主要方式仍是内吞作用^[27].

1.4 ENPs-鱼类

鱼类一方面可以通过水体直接摄取ENPs,另一方面可以通过捕食作用摄食暴露了ENPs的水生植物以及无脊椎动物. ENPs在鱼体内的分布直接影响人类的生命健康.图2阐述了ENPs在鱼体内的分布: ENPs通过摄食作用进入体内(图2, 过程①),其中进入消化道的金属ENPs会通过胃酸释放金属离子,离子通过小肠上皮细胞转移到各个器官,包括心脏、肝脏、脾脏、肾脏、胆囊等,甚至可以进入到脑(图2)^[36].分布在各个器官的ENPs,会对鱼类产生一定的损伤.例如, ENPs可以通过鱼类的吞噬细胞进入鱼类的血液,造成血小板凝结,影响生长和发育^[37].由于肝脏是生物体最大的解毒器官,脾脏是最重要的免疫器官,所以外源污染物可能在肝脏和脾脏中大量的蓄积^[38]. TiO_2 ENPs暴露的鲤鱼,检测到肝脏细胞的凋亡以及肝脏坏死^[39]. ENPs还会分布在生殖腺上,使受精卵、胚胎受损^[40],对生物后代造成更大的潜在威

图2 ENPs在鱼体内的分布

Figure 2 The distribution of ENPs in the fish

胁。ENPs通过消化后,会被排出体外,重新进入环境,对水生环境造成潜在的二次威胁^[41]。此外ENPs可以通过鳃的呼吸作用吸附在鳃分泌的黏液保护层上(图2,过程②),例如鳟鱼可以通过鳃分泌的黏液吸附水中的多壁碳纳米管^[42]。ENPs还可以穿过黏液层到达鳃的上皮细胞,通过细胞的内吞作用到达鱼的体内;同时,吸附在鳃上的ENPs会发生解吸,重新回归到环境中。皮肤表面分泌的黏液可以使ENPs吸附在皮肤表面^[43](图2,过程③),接着再通过布朗运动穿过黏液层通过静电引力等作用与皮肤上的蛋白相结合。鱼表面的鱼鳞也能够为ENPs提供吸附位点。

综上所述,ENPs作用于不同的水生生物,其体内分布存在明显差异;ENPs在不同营养级上的分布以及在生物体内的蓄积直接影响ENPs沿整个食物链(网)的传递,甚至对人类健康造成严重威胁。

2 ENPs在食物链上的传递

ENPs进入水生环境后,不仅会直接在不同的生物体内分布,还会间接地通过捕食与被捕食过程由低营养级到高营养级传递,并且在食物链上发生生物放大,最终会危害人类健康,因此研究ENPs的传递效应亦显得尤为重要。表S1归纳了近年来ENPs在不同水生食物链中的研究。

根据表S1,可以归纳出以下几点结论:(1)对不同类型的食物链的研究表明,不同种类ENPs能够经营养级进行传递,在低营养级生物体内的ENPs,通过摄食传递到高营养级生物体。一般情况下,水体暴露的生物体内ENPs的含量要高于膳食暴露。但是无论哪种暴露方式,对于鱼类等捕食者而言,ENPs主要分布在消化器官中,在其他器官例如鳃、肝脏、脾等中也有ENPs的分布,甚至可以传递到脑、血液等,对整个生物物种乃至食物链(网)造成严重威胁。(2)高营养级的生物摄入由低营养级生物携带的ENPs后,能通过其自身代谢将大部分的ENPs排出体外,ENPs随排泄物重新进入环境,可能会对其他滤食性及杂食性生物造成生态风险。(3)迄今为止,关于ENPs在水生食物链上发生生物放大效应的研究报道仅有3篇,多数的研究证实并未发生生物放大效应。发生生物放大的机制主要有:①特殊的食物链结构。以底栖生物为例,沙蚕等底栖生物对沉积在底泥中的ENPs蓄积量很大,以此类物为第一营养剂的食物链

中,ENPs的营养传递和生物放大现象都会受到相应影响^[44];②ENPs的性质。一些金属ENPs会通过释放离子增加在体内的积累,这种累积与金属种类有关,如一些生物必须的金属元素锌、铁等,生物膜表面有专属运输通道,更有利于生物的吸收^[45,46]。目前关于重金属在食物链上的研究表明重金属更容易与生物蛋白发生螯合等作用,在体内产生积累,进而产生生物放大现象^[47]。另外亲脂性较强的ENPs才可能会在体内产生生物积累;③水化学条件的影响。例如低的pH所导致的离子释放(以及与水体中天然有机质(natural organic matter, NOM)的结合所造成的影响)也会影响生物放大效应^[48];④捕食者与被捕食者的消化生理学差异。ENPs在被捕食者体内的停留时间较长,还未将ENPs排出体外就被捕食者摄食^[49]。

3 ENPs沿水生食物链传递的影响因素

不同的ENPs在不同水环境下会发生各种物理化学变化,进而影响生物可得性及生物可利用性,从而影响ENPs在食物链上的传递。图3表述了ENPs沿水生食物链传递的影响因素。

3.1 水环境介质对ENPs沿食物链传递过程的影响

(i) 光照。一些ENPs具有与生俱来的光学活性,例如金属ENPs^[50]、碳材料、红磷^[51]、氮化碳^[52]等会形成能带结构,提供的光能达到一定程度后,就可以引起电子跃迁,当这些材料进入水环境,在氧气以及水分子作用下产生自由基,改变ENPs的性质。ENPs在水中发生光化学反应后,会在表面形成活性氧(reactive oxygen species, ROS),使ENPs发生转化(如含氧官能团增多,增加表面负电荷),团聚沉降性能发生变化,从而改变了ENPs的生物可利用性。Hu等人^[53]研究指出石墨烯在水环境中发生转化,含氧官能团增多,表面负电荷增加,从而增加与藻的静电斥力,使生物可利用性减小。Chowdhury等人^[54]表明光照会使氧化石墨烯发生光降解从而更加碎片化,尺寸减小,比表面积增大,更易与细胞接触而进入细胞,从而增加了生物可得性(图3,过程①)。但是目前关于降解产物与生物相互作用的研究还很少,还未见降解产物沿食物链的报道。

(ii) 水体的pH。水体的pH直接影响ENPs的表面电荷。不同的纳米颗粒具有不同的等电点(zero point charge, ZPC),当pH<ZPC时,ENPs表面带正电;

图3 ENPs沿水生食物链传递的影响因素

Figure 3 Factors that influence the transfer of ENPs along the aquatic food chains

当 $\text{pH} > \text{ZPC}$ 时, ENPs表面带负电, 例如Ag ENPs在 $\text{pH} < 8$ 时带正电, 与表面带负电的绿藻通过静电引力吸附在藻表面; 当 $\text{pH} > 8$ 时, 因为静电斥力减小了与藻的接触^[55]. 另外, 水体的pH会改变ENPs的离子释放能力, 间接地影响ENPs在生物体中的积累^[56](图3, 过程②).

(iii) 水体中的其他物质. 天然水体是一个非常复杂的系统, 一旦ENPs进入水体, 会与水体中人为排放的污染物(有机污染物、重金属)以及NOM相互作用, 对生物体的摄食产生联合效应^[57]. ENPs高的比表面积可以吸附水中的无机离子(例如“特洛伊木马效应”)(图3, 过程③), 增加重金属的生物可利用度. 例如 C_{60} 促进了砷在斑马鱼肝脏中的积累^[58]; TiO_2 ENPs增加了大型溞体内镉的含量^[59]. 一方面, 水体中的NOM可以吸附在ENPs表面(图3, 过程④), 使得ENPs电负性增加, 例如水中腐殖酸(humic Acid, HA)增加了 TiO_2 ENPs表面的负电荷, 抑制ENPs与藻的接触^[60]. 另一方面, NOM可以减少ENPs同相团聚, 增加其稳定性, 使浮游生物的生物可得性增强. CeO_2 ENPs表面附着上NOM, 大大增加了其悬浮稳定

性^[61]; 另外Park等人^[48]研究表明有机污染物17 α -乙炔雌二醇的存在使得 C_{60} 的悬浮稳定性增强, 增强了丰年虾对ENPs的生物可得性, 继而被斑马鱼摄食, 使ENPs分布在高营养级体内; 另有研究证明NOM促进了 CuO ENPs释放出更多的 Cu^{2+} , 增加藻的生物可利用性^[62].

(iv) 离子强度. 高离子强度(ionic strength, I.S.)会压缩ENPs表面的双电层, 例如 Ca^{2+} 的存在可以压缩 ZnO , NiO , TiO_2 , Fe_2O_3 及 SiO_2 ENPs表面的双电层, 使ENPs之间静电斥力减小, 发生团聚, 造成ENPs发生沉降(图3, 过程⑤)^[63]. 在海洋环境中, 由于离子强度大, ENPs的悬浮性差, 容易发生团聚沉降, 进而减小浮游生物对其的摄取, 增强了沉积环境中生物的可得性, 使得ENPs更易在底栖食物链中传递. 此外, ENPs的团聚限制了颗粒与生物的直接接触, 增大了ENPs进入细胞的难度^[64].

(v) 水体的氧化还原电位. 水体的氧化还原电位(oxidation-reduction potential, ORP)会影响ENPs的转化, 从而改变了生物的有效利用(图3, 过程⑥). 如果ORP较高, 会使ENPs发生氧化; 反之, 则使ENPs

发生还原. 例如碳材料在水环境下, 由于水合等作用, 使ENPs发生氧化还原反应, 表面羟基、羧基等官能团增多, 表面负电荷增多, 从而减小生物的有效利用^[54]. 目前已经报道Ag ENPs转化成 Ag_2S ^[65]后, 能够减小其生物利用度. CuO ENPs进入沉积环境时, 随着ORP的降低会转化成非常稳定的Cu-针铁矿及 Cu_2S , 从而减少了ENPs在水稻体内的生物可利用性^[66].

2.2 ENPs的性质对食物链传递过程的影响

(i) ENPs溶解. 对于在水环境下容易发生溶解的ENPs, 释放的离子可以通过细胞膜上的膜转运蛋白直接运输到细胞内部, 从而造成ENPs和溶解的离子共同沿着食物链进行传递(图3, 过程⑦). Kalman等人^[56]通过研究Ag ENPs沿着小球藻(*C. vulgaris*)到大型蚤(*D. magnai*)二级食物链的传递过程, 表明Ag ENPs的溶解提高了其生物可得性, 通过膳食暴露, 在大型蚤消化道中检测到Ag的存在. 一旦ENPs转化成离子, 就更容易与生物体相互作用, 影响生物摄食和在体内的分布与积累, 从而影响其食物链传递.

(ii) ENPs的表面性质. 生物以及ENPs的表面电荷是影响ENPs与生物的界面作用关键因素. 微生物细胞壁及细胞膜通常带负电, 因此带正电的ENPs更容易与细胞接触而内化(图3, 过程⑧). 例如带正电的 CeO_2 ENPs在秀丽线虫(*Caenorhabditis elegans*)体内的含量大于带负电的 CeO_2 ENPs^[67]. 一些疏水性较强或者高离子强度水体中的ENPs非常容易团聚, 发生沉降, 使底栖生物对ENPs的生物可得性增强. 这类ENPs在生产过程中通常会添加柠檬酸等^[68]表面活性剂增加其悬浮稳定性, 改变了其环境归趋^[69], 并且表面包裹的有机物在水溶液中容易形成氢键, 决定了ENPs与生物的反应位点^[70]. Skjolding等人^[45]将表面包裹不同涂层的ENPs进行食物链暴露, 发现表面涂层使得大型蚤对ENPs的摄食及净化产生差异, 辛基包裹的 ZnO ENPs的疏水性大于未经包裹的, 使包裹之后的ENPs亲脂性增强, 增加了生物的可利用性, 进而使斑马鱼通过捕食作用摄入大型蚤后体内的Zn含量出现差异性. 表面包裹还会改变ENPs的表面电荷, 使其与生物的接触发生改变. 另外由于海浪等的动力学作用, 悬浮的ENPs很容易随水体发生迁移^[71], 增强了其对悬浮生物的生物可得性, 从而使得底栖食物链中ENPs的传递减少.

(iii) ENPs的粒径和形状. 因为小尺寸颗粒的迁移率快、靶生物表面界面相互作用的能量位垒低^[72]、比表面积较大以及吸附速率较高^[73], ENPs尺寸越小越容易进入细胞, 从而使ENPs更容易被细胞内化, 在生物体内积累, 进而发生生物传递^[74](图3, 过程⑨). Zhang等人^[75]将金鱼藻暴露于7 nm的 CeO_2 ENPs 15天后, 50%的ENPs进入藻细胞, 而经25 nm的 CeO_2 ENPs暴露后, 仅有3%的ENPs进入藻细胞. 不同的形状的ENPs对生物的作用也是不同的(图3, 过程⑩), 例如三角形Ag ENPs与大肠杆菌接触要大于其球形和棒状^[76]; 此外, 相较Ag纳米线, Ag纳米片由于其锋利的边缘更容易切割细胞, 进入细胞内部^[77]. 目前还未见关于不同形状的ENPs对食物链的研究, 需要进一步进行探讨.

3 展望与挑战

目前关于ENPs对水生生物的研究已有了很大的进展, ENPs在水生环境中的分布是影响其在食物链中传递的关键. 迄今为止, ENPs沿食物链传递的研究还较少, 尤其是关于海洋环境中的研究还是处于初步阶段, 我们对这一领域的研究工作进行了展望: (1) ENPs在生物体内分布、迁移转化的研究通常利用的是常规的研究技术手段, 主要包括原子分光光度计、电感耦合等离子体质谱、透射电子显微镜、扫描电子显微镜等^[44,78]. 这些传统手段的检测和分析仪器在ENPs的生物转化方面的研究存在很大局限性, 不能对ENPs的结构和化学形态进行准确的分析. 同步辐射近边吸收技术是目前国际公认的探索金属ENPs生物转化的较为前沿的技术, 可以在不破坏细胞和其他生物样品结构的条件下, 最大限度地保留待测元素在生物组织和细胞中的状态, 探明ENPs在生物内的分布和存在形式, 但是测定成本很高; 单颗粒-电感耦合等离子体质谱(ICP-MS)可以原位测定ENPs的浓度^[79], 但是当ENPs的尺寸大于20 nm, 应用受到限制, 因此更先进有效的测定手段还有待被设计. 碳纳米材料一般选择同位素标记或荧光标记的手段来进行检测, 但其操作繁琐, 成本高昂, 因此需要寻得一种简便高效的手段, 如共聚焦显微镜与拉曼联用技术, 可以有效地通过图像和数据相结合的方法探究碳纳米材料在环境中的归趋; 此外色谱-质谱联用技术作为一种高效、灵敏的检测手段^[80], 在ENPs在生物体内分布、迁移转化的研究中有较好的应用前景.

(2) ENPs在食物链中的研究主要集中于二级食物链上,不能完全反映真实复杂的生物系统,因此需要建立完整的实验条件,对生态系统中ENPs的生物效应进行更为系统和全面的探究.另外,关于海洋食物链的研究迄今仅有十几篇的报道,主要是基于实验室条件下进行研究的,在实际环境中,水介质成分多样,水生食物链(网)关系复杂,原位而非实验室模拟条件下ENPs在食物链中的传递的研究需要加倍关注.

(3) 实验室条件下的研究表明ENPs能够沿食物链传

递,但大部分没有生物放大效应,主要是由于生物自身的生理生化作用会将一些外来污染物排出体外.但是在实际环境中,ENPs随排泄物重新进入环境,可能会对其他滤食性及杂食性生物造成生态风险,需进一步探讨.

(4) 由于ENPs可以通过改性等处理方式降低生物可利用性,因此在排放到环境前需要制定相应的法律法规,建立ENPs生物风险评估体系及环境标准,使其在排放前进行预处理,从而从根源上降低生态风险.

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补充材料

表 S1 ENPs 沿不同水生食物链的传递效应

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Summary for “人工合成纳米颗粒在水生食物链中的分布、传递及其影响因素”

Distribution and trophic transfer of engineered nanoparticles along aquatic food chains and related influencing factors: A review

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Nanotechnology is developing rapidly and has been widely applied in chemical engineering, electronic engineering, energy sources, environmental protection and other fields. Engineered nanoparticles (ENPs) are inevitably releasing into the aquatic environment during the entire life cycle of nano-products, thus exposing to aquatic organisms, which has been well investigated in the past decade. ENPs could be internalized by different types of aquatic organisms including algae, plants, and fish. Therefore, the possible transfer of ENPs between different aquatic organisms has attracted attentions, and many important publications reported the trophic transfer of ENPs through aquatic food chains. This review first provided the internalization and distribution of ENPs in different aquatic organisms including microorganism, aquatic plants, invertebrate and fish: (1) For microorganisms, ENPs are mainly adsorbed on the cellular surface, and then be internalized, and the internalization could lead to subsequent toxicity; (2) ENPs could be taken up by the roots of aquatic plants, and then be migrated to stem and leaves by evapotranspiration; (3) ENPs were mainly located in the hepatopancreas and gut of invertebrates; (4) ENPs could be accumulated in the gill and digestive tract of fish, and then distributed into other tissues such as liver and spleen. Secondly, the research status of ENPs in aquatic food chain were summarized and analyzed. The transfer of ENPs was observed in both freshwater and marine food chains, and current investigations on freshwater food chains contributed a larger proportion than in the marine. Most of the researches proved that ENPs can transfer along the food chain, but the biomagnification was only reported in a few publications. Thirdly, the influence of water chemistry factors and ENPs properties on the transfer of ENPs via aquatic food chains was discussed. For the water chemistry factors, like light illumination, solution pH, co-existing compounds such as natural organic matter, ionic strength, and oxidation–reduction potential all altered the bioavailability of ENPs and played important roles in the trophic transfer of ENPs. For the properties of ENPs, it is observed that: (1) the metal ions which were released from metal-containing ENPs can improve the bioavailability of ENPs in aquatic organisms; (2) different coatings of ENPs brought different or opposite surface charge on the surface, thus changing the internalization and bioavailability of ENPs. For example, ENPs with positively charged surface could be easily adsorbed on the surface of aquatic organisms than the negatively charged particles; (3) different size and shape influenced the contacting area between the ENPs and organisms, and ENPs with smaller size were usually more readily enter aquatic organisms, which were deeply discussed in this review. Finally, the current researches, prospects and challenges on ENPs transfer in the aquatic food chains are addressed.

engineered nanoparticles, bio-distribution, aquatic food chain, trophic transfer, biomagnification

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