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放射性核素在农业资源与环境中应用研究现状与展望

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摘要: 放射性核素应用领域广、分析效率高, 有效推动了多学科交叉领域的创新发展, 是现代科技和工程领域中不可或缺的重要工具。为深入了解近年来放射性核素在农业相关领域的应用研究现状, 本研究聚焦其在国内外植物辐射诱变育种、植物保护和水土保持中的研究进展, 主要介绍农作物育种与植物病虫害防治, 氮磷营养元素界面迁移、土壤侵蚀防治等领域放射性核素示踪技术的应用研究, 以及放射性核素的智能分析。同时, 基于当前放射性核素技术在该领域研究中面临的问题, 结合现代质谱技术的发展、新型放射性同位素的研发、多学科交叉融合等带来的挑战和机遇, 对放射性核素技术的未来发展与应用提出展望。

关键词: 放射性核素; 辐射育种; 植物病虫害; 同位素示踪; 土壤侵蚀
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Research Status and Prospect of the Application of Radionuclides in Agricultural Resources and Environment

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Abstract: Radionuclides with a diverse range of applications and high analytical efficiency to promote multidisciplinary Innovation and developments, which are considered to be an essential tool in the field of modern science and engineering. To gain a deeper understanding of the current state of research on the application of radioactive isotopes technology in agricultural-related fields in recent years, this paper focuses on its research progress in radiation-induced mutagenesis breeding for plants, plant protection, soil and water conservation, both domestically and internationally. It mainly introduces the applications of radioactive isotopes in crop breeding and pest control, tracer technologies for the migration of nutrient elements of nitrogen and phosphorus at soil-plant-

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microorganism interfaces and at soil-water interfaces to prevent soil erosion, as well as the intelligent analysis of radioactive nuclides. Based on the current challenges faced by radionuclide technology in this field, along with the development of modern mass spectrometry technology, the research and development of new radioactive isotopes, and the challenges and opportunities brought by interdisciplinary integration, this paper presents prospects for the future development and application of radionuclide technology.

Key words: radionuclides; radiation breeding; plant disease and pest control; isotope tracing; soil erosion

自然界中大多数元素都以质子数相同而中子数不同的同位素形式存在。放射性核素原子核中不平衡的质子和中子比例导致其自发地释放出α(氦核,质量最大,穿透能力差)、β(电子)、γ(光子)粒子衰变成稳定的元素,并形成对应的三种类型的辐射射线[1]。可控的氘氚核聚变不但能产生高能α粒子,还是巨大的中子源,成为近年来的研究热点[2-3]。高能射线能够通过能量传递引起生物机体中的分子发生结构变化,触发化学反应,从而改变生物体的结构和功能[4-6]。通常使用线性能量转移(又称传能线密度,LET)来度量辐射穿过介质时传递给介质的能量,及其对生物样本介质的影响。相比β和γ低LET射线,α射线和中子射线具有较高的LET,会对生物系统造成更严重的辐射损伤以及更复杂的生物效应[7-9]。进而引入"相对生物效应"(RBE)概念来评估其对生物体的损伤程度和暴露风险[10]。本研究聚焦放射性核素在农业资源与生态环境中的应用与发展现状,包括其在辐射育种、植物病虫害防治、面源污染和土壤侵蚀同位素示踪、人工智能(AI)助力核辐射数据分析等方面发挥的重大作用,并对该技术面临的挑战和未来发展进行了讨论和展望。

1 辐射诱变育种机理及研究现状

辐射突变育种过程始于辐射和DNA之间的相互作用,包括通过辐射能改变电子结构使得化学键断裂,直接改变DNA分子结构和遗传功能,以及通过电离辐射作用于水分子产生的自由基,造成间接氧化损伤[4, 11]。电离辐射是一种高能辐射,产生的中间离子和自由基(如H^+、羟基自由基OH、超氧自由基O_2^-等)会破坏遗传物质,导致基因组不稳定[12-14]。辐射诱导的DNA损伤类型包括碱基损伤(氧化损伤、交联、嘧啶二聚体)、无碱基(AP)位点、单链断裂(SSB)和双链断裂(DSB)等,其中DSB最难修复且对细胞最有威胁,并且会损害基因组稳定性[14-17]。由多个DNA损伤组成的簇状DNA损伤(CDD)是电离辐射的一个特征,其修复困难,被认为是电离辐射有害影响的主要原因[18-19]。CDD本质复杂,通常可以归类为复杂的DSB或非DSB簇,其频率和复杂性随着LET的增加而增加。一般来说,成簇的DNA损伤会导致突变频率增加[7, 15, 20]。为了保持基因组稳定性,细胞已经进化出一套复杂的机制来修复各种类型的DNA损伤,即DNA损伤应答(DDR)[21-22]。当DNA损伤被错误修复时就会引发基因突变,氧化碱基损伤、AP位点和SSB主要通过碱基切除途径进行修复(BER)[7, 23],核苷酸切除修复(NER)可处理嘧啶二聚体和某些DNA交联[17, 24],DSB修复主要有非同源末端连接(NHEJ)和同源重组(HR)两种不同机制[21, 25],而错配修复(MMR)可以识别并修复DNA复制和重组过程中可能出现的碱基错配、缺失和错误插入[15]。图1展示了辐射造成的不同DNA损伤类型及其修复机制。

放射性核素^{60}Co(水介质中LET约为0.2 keV/μm)和^{137}Cs(水介质中LET<0.2 keV/μm)产生的γ射线源,波长在0.01 nm以下,具有很强穿透力,是辐射诱变育种中最常用的物理诱变剂[26-27]。此外,农业上通常通过注射、浸泡等技术处理,将放射性同位素(如^{32}P和^{35}S)引入植物材料,其产生的β射线(在水介质中,^{32}P LET约0.28 keV/μm, ^{35}S LET约0.17 keV/μm)对细胞组织起到内照射作用(图2)。低LET的γ、β射线主要通过水产生的自由基间接引起DNA碱基损伤和SSB,通常很容易修复[7]。与γ射线相比,β射线具有更高的LET值,可以在更局部的

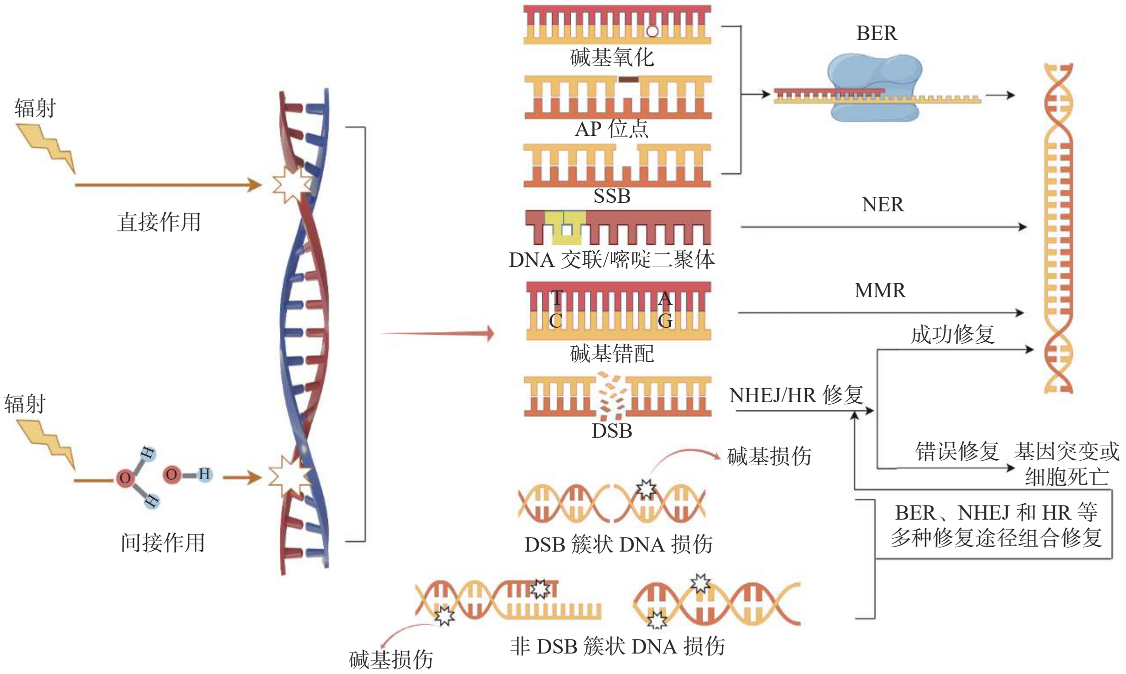

图 1　辐射诱导的不同 DNA 损伤及其修复机制(本图由 Figdraw 绘制)

Fig.1　Different radiation-induced DNA damage and its repair mechanisms (By Figdraw)

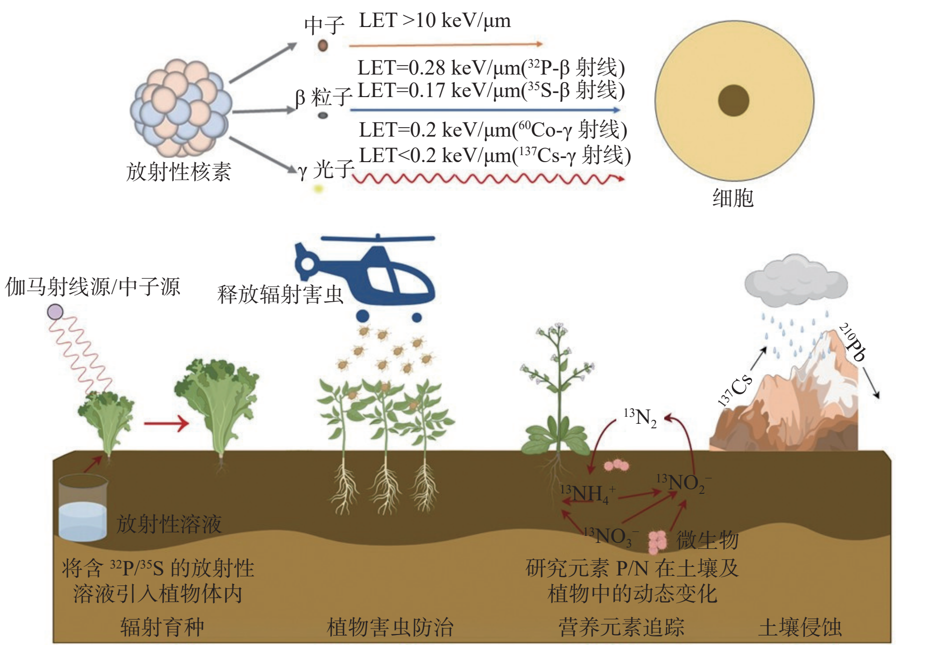

图 2　放射性核素在农业资源与环境中的应用(本图由 Figdraw 绘制)

Fig.2　Application of radionuclides in agricultural resources and environment (By Figdraw)

区域引入广泛的DNA损伤,提高了育种突变率。但是内照射方式可能导致植物受到不均匀的辐射,从而产生辐射损伤或突变效果不一致的问题。而且经过内辐射的植物材料具放射性,对周围的污染较大,限制了其应用与推广。γ射线因其诱变安全、处理简便、易于控制辐射条件等优势使其广泛应用于辐射育种领域。近年来,中子发生器研制的发展推动了中子辐照育种研究开展(图 2)。中子射线是一种高 LET 射线(水介质中 LET>10 keV/μm),本身不会引起电离,主要与原子核发生作用产生粒子,带有一定能量的粒子会引起电离产生生物学效应。

与γ射线辐射相比，中子辐射具有穿透性强、突变谱宽、变异率高、变异后代特征相对稳定的特点，可以产生更明显而且更高的辐射生物效应[28]。

据统计，截止到目前，70多个国家利用诱变技术在210多种植物上育成的3300多个突变品种（包括多种作物、观赏植物和树木）已被登记，用于商业用途，其中约有一半是利用γ射线创造的（Mutant Variety Database - Home (iaea.org)）。尽管如此，有益突变频率较低、突变随机性较大等一直是辐射诱变育种所面临的问题[11, 29]。随着近年来以CRISPR（clustered regularly interspaced short palindromic repeat）技术为代表的靶向基因编辑技术等先进突变技术的发展，给传统育种方法带来了巨大的挑战[30]，这可能是2010年后IAEA突变品种数据库(Mutant Variety Database)中登记品种数量急剧下降的原因[11]。利用诱变技术产生的变异是由其内部遗传物质发生重组和突变产生，属于生物体内源基因的自身诱变改良，不存在基因安全性问题。因此，有必要持续深入推进辐射诱变育种机制研究与技术开发。鉴定和筛选辐射诱变引起的遗传变异是育种的关键。近年来，现代高通量仪器的发展及其与分子标记技术的结合，可用于连续多代诱变群体的基因型和表型的高通量鉴定，有利于在分子水平上阐明辐射诱变机制，推动育种技术的高效、准确、系统化发展[11, 31-33]。诱变育种与现代分子生物学技术、基因编辑技术以及基因组学的结合，提高了突变体鉴别筛选及选择效率，加强了定向诱变并扩大了突变谱[6, 33-34]，是突变育种目前主要发展趋势和研究热点。总之，通过依靠先进辐射设备的发展，结合高通量基因测序和其他先进的分子生物技术，辐射诱变效应有望实现可预测，使研究朝着定向诱变方向发展，共同推动现代农业植物育种技术进步。

2 辐射不育与植物病虫害防治

近年来，随着气候变化、耕作栽培方式改变和农作物复种指数提高，农作物病虫害呈多发、频发态势，重大农作物病虫害时有发生。昆虫辐射不育技术（SIT）是一种环境友好的大面积植物害虫治理方法，通过大规模饲养目标昆虫（主要是雄虫），然后利用电离辐射将其绝育，并在目标区域内将不育昆虫释放，与野生种群交配，但无后代产生，从而逐渐减少害虫数量[35]（图1）。SIT的成功取决于被释放昆虫的有效绝育，以及这些昆虫与它们的野外同伴竞争配偶交配的能力[35-36]。辐射诱导的不育是受体生殖细胞中由电离辐射引起的染色体结构变异的结果[37-38]。^{60}Co仍然是辐射不育技术最广泛使用的辐射源，而^{137}Cs由于稳定性较低以及穿透力较弱基本被淘汰[35]。自从1930年代Knipling提出雄性不育可以用来减少或清除特定害虫的野生种群之后，棉铃红虫、苹果蠹蛾等农业害虫得到了成功的根除、抑制或控制[35]。现阶段国家在粮食和环境安全方面不断加大投入力度，SIT符合现代农业病虫害绿色防控理念，对保障粮食安全和人民健康具有重要意义。

然而，SIT具有不可避免的局限性，辐照过程有时会大大降低被释放害虫的活力和交配竞争力[37, 39]。高剂量γ射线辐照，可诱导目标害虫不育，例如鳞翅目对电离辐射的高抗辐射性，需要高剂量γ射线才能诱导其不育，但这种完全不育剂量除了造成预期的遗传损伤外，还会造成各种生理缺陷，降低与野外种群争夺配偶的能力[40]。亚不育剂量（半不育剂量）是SIT技术的一大突破，其可使接受辐照的害虫部分不育，并可将不育性遗传到后代，即遗传不育（图3）。而且与完全不育剂量相比，经过亚不育剂量处理后的害虫竞争配偶能力和生殖力得到了提高[41-42]，但还是会对昆虫造成伤害。因此，辐照处理后能保证昆虫最大限度的存活率、生殖力和交配竞争力以及大规模的释放对作物、环境等不产生特别严重的影响是在进行SIT时需要考虑的问题[43-44]。同时，对于SIT计划，在大规模饲养设施中对昆虫进行有效的性别分离和仅释放雄性是提高昆虫不育效率的重

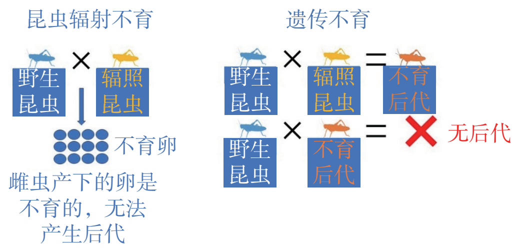

图3 昆虫辐射不育与遗传不育

Fig.3 Radiation sterility and genetic sterility in insects

要因素,需重复释放大量昆虫的必要性也是传统 SIT 的潜在缺点[45]。

目前已经出现了与其他防治方法结合可以克服 SIT 的不足,例如基于沃尔巴克氏体的不相容昆虫技术(IIT)与 SIT 结合使用[46],低辐射剂量可使雌性完全不育,而雄性的不育是由沃尔巴克氏体感染和低辐射剂量引起。IIT 严格要求不释放受感染的雌性,这在野外不可能实现[47]。IIT 和 SIT 的结合可以改善各自缺点,受到不影响活力的低辐射剂量照射时,雌性会完全不育,从而大大降低感染雌雄产生可育后代的可能性。因此,多种防控措施的结合是未来植物病虫害防治发展的方向。同时,随着基因组测序、基因工程和基因编辑技术的发展,针对特定目标基因和害虫种群的遗传控制技术具有广阔的发展前景。近年来,研究人员展开了大量研究,结合转基因以及基因编辑技术精准靶向生殖发育相关基因,可以有效解决传统 SIT 面临的问题,例如基于 CRISPR/ Cas9 的新型基因编辑技术,就是目前植物病虫害防治研究的热点,其很好地解决了不育昆虫竞争交配能力降低和性别筛选复杂等问题[45, 47-50]。

3　放射性核素养分示踪与农业面源污染防治

农业放射性同位素示踪技术就是以放射性核素取代化合物分子的一种或几种原子用作示踪剂,观察由放射性核素标记的物质的分布和变化情况,探讨被追踪物质在植物或动物体内及周围环境中的迁移、转化、运输、吸收和代谢规律等[51]。伴随着同位素分析技术的发展,放射性核素示踪技术在植物营养和土壤科学研究方面发挥了重要作用。农田氮磷养分流失是我国农业面源污染的主要污染源,也是国内外一直致力解决的农业环境问题。磷是植物正常生长发育的一种必需元素,尽管土壤全磷含量通常在 0.02% ~ 0.15% 之间,但大部分磷植物不可利用,因此磷是作物生产中的限制性养分[52-53]。施用磷肥虽然能有效缓解土壤磷不足的问题,但无机磷在酸性土壤中随铁和铝氧化物沉淀,或在中性和碱性土壤中钙沉淀,或被所有 pH 范围内的粘土矿物吸收,造成了土壤磷流失[54-55]。土壤中有机磷在矿化后才能被植物吸收利用,而微生物也能吸收一部分可溶性有机磷,土壤磷有效性取决于总磷含量以及吸附、解吸、沉淀、溶解、矿化和固定过程之间的平衡[56]。磷肥的利用率低和施用量大造成农业面源环境污染,是当前生态环境保护工作的突出难点[52, 55, 57]。因此,明确磷在土壤和作物之间的迁移机制,提高作物对土壤中磷元素的吸收和利用具有重要意义。

目前已利用放射性同位素(^{32}P 和 ^{33}P)标记来追踪磷在土壤-植物-微生物系统中的动态变化以及不同条件下植物-微生物对土壤磷的竞争展开了大量研究[56, 58-60](图 2)。通过对磷在土壤中以及微生物利用的变化过程及其有效性的认识,对制定合适的磷管理策略至关重要。但是,施用矿物磷肥同时会导致耕地表层土壤中重金属镉(Cd)的积累,并通过食物链进一步危害人体健康[61-64]。中国耕地 Cd 污染物点位超标率已经达到 7.0%,尽管放射性同位素 ^{109}Cd 追踪发现仅有小部分被生菜/小麦所吸收,土壤中大量残留的 Cd(约 98%)会显著增加高富集作物品种(如水稻)和食物链中 Cd 的输入[61-62, 65-66]。另外,磷放射性同位素半衰期短,限制了磷在生态系统中行为和过程的长期追踪研究。目前,根据不同植物对利用土壤磷不同,筛选和培养磷高效利用基因型作物的育种技术有可能成为代替传统施用磷肥来改良土壤磷不足的重要方法之一[67-68]。利用磷的放射性同位素示踪技术可为磷高效利用基因型植物的选育提供参考。

氮是植物生长的重要营养物质,植物以硝酸盐和铵态氮的形式吸收无机氮,但在某些土壤、环境和植物物种中,植物根部对氨基酸和其他有机氮化合物的吸收也起着重要作用[69]。同时,氮通常也是陆生植物最有限的营养物质,因为植物可利用的氮形式在土壤中非常不稳定,植物严重依赖生物固氮来补充土壤中通过淋溶、径流、反硝化、氨化和厌氧氨氧化产生的气体而流失的氮[70-71]。大量施用氮肥可以确保作物最大产量生产,但施用氮肥成本昂贵,而且会对环境产生负面影响[69, 72]。特别是近年来对反硝化(即 $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$)释放强效温室气体 N_2O(单位分子增温潜力是 CO_2 的 300 倍)的关注度极高[73-75]。土壤 N_2O 排放

通常随着氮肥施用量的增加而增加，且受多种环境因素影响，全球 N_2O 排放量预计将持续增加[76-77]。因此，简单地增加施肥并不是一个农业可持续发展的解决方案，研究陆地生态系统氮循环具有重要意义[78]。

^{13}N 放射性示踪技术是一种独特的技术手段，其在阐明氮肥施用和环境因素对氮循环影响、温室气体减排研究以及确定农业管理措施中均发挥了重要作用。由于其放射性，^{13}N 能够实现高灵敏度和非侵入性检测，已被广泛用于追踪各种条件下氮的分配及其动态变化，有效揭示了作物营养元素的转化机理[79-83]，为主要作物的高产、优产提供了重要的科学依据和技术支撑。而且随着高通量表型平台的发展，正电子发射断层扫描（PET）和正电子发射示踪成像系统（PETIS）等成像方法的使用在环境科学中得到了极大的扩展。^{13}N 是正电子发射核素，当正电子衰变时，它会向相反的方向发射两条易于检测的 γ 射线。通过发射的 γ 射线来追踪正电子发射核素，可以可视化正电子发射核素的分布[83]。

4 土壤侵蚀检测与土壤资源可持续利用

土壤是一种不可再生的资源，保护土壤对于粮食安全至关重要。土壤侵蚀是指水、风等自然因素或人类活动导致土壤表层逐渐剥蚀和迁移的过程。肥沃的表层土壤被侵蚀后，不仅导致土地生产力下降，还可能导致水源污染和生态平衡破坏[84]。评估土壤侵蚀速率变化对于防止土地退化至关重要，使用 ^{137}Cs、^{210}Pb、^{7}Be 和 $^{239+240}Pu$ 等放射性核素示踪（表 1）是研究土壤侵蚀的一种方便、高效的方法[85]（图 2）。

表 1 土壤侵蚀常用放射性同位素

Table 1 Radioisotopes commonly used in soil erosion

放射性核素	半衰期	来源	特点
^{137}Cs	30.2 a	原子核试验	技术相对成熟，但因其半衰期较短，连续衰变导致很快达到其检测极限。
^{210}Pb	22.3 a	天然放射性核素 ^{226}Ra 的衰变	可以评估更长时间尺度，但具有高度不确定性。
^{7}Be	53.3 d	宇宙射线与大气中存在的氮、碳和氧原子的散裂反应。	用于评估发生在几个月时间尺度内或者单次强降雨的侵蚀沉积过程，但半衰期很短，无法深入较深土壤研究。
$^{239+240}Pu$	4 110 a（^{239}Pu） 6 561 a（^{240}Pu）	原子核试验	测量更灵敏，是代替 ^{137}Cs 理想的示踪剂。

二十世纪五十和六十年代的人工核试验使 ^{137}Cs 广泛散布到全球环境，随后 ^{137}Cs 通过大气降水输入陆地表面，进而被土壤细颗粒迅速强烈吸附，并跟随土壤颗粒在环境中迁移，这为测量土壤侵蚀速率和空间变化提供了有效工具[85-87]。通过将调查区域土壤 ^{137}Cs 含量与当地参考值比较，可以确定调查区域为侵蚀区或沉积区，还可通过相关模型估算该区域的侵蚀量与侵蚀速度[85]。^{137}Cs 示踪剂在土壤侵蚀研究中的应用经历了较长时间的发展已经相对成熟。然而，来源单一、缺乏供应、半衰期短、连续衰变等特点使 ^{137}Cs 越来越难以在土壤样本中检测到[86, 88]。长寿命核素 Pu 与 ^{137}Cs 来源相同，半衰期比 ^{137}Cs 更长，测量更灵敏，不仅可以与更细的土壤颗粒相结合，还与有机质和氧化物结合，是代替 ^{137}Cs 理想的研究土壤侵蚀的示踪剂[85-86, 89-90]。天然放射性核素 ^{210}Pb 和 ^{7}Be 分别来源于 ^{226}Ra 衰变，和宇宙射线与大气中存在的氮、碳和氧原子的散裂反应[91]。在土壤侵蚀和沉积研究中应用这些天然放射性核素的基本原理与人工放射性核素 ^{137}Cs 相似[92]。有时为了提高土壤侵蚀速率的准确性，会采用复合核素示踪技术[88, 93]。^{137}Cs 一般可以评估五十年来土壤发生的侵蚀或沉积过程，^{210}Pb 具有百年时间尺度积计年的重要价值。而 ^{7}Be 可以评估发生在几个月时间尺度内或者单次强降雨的侵蚀沉积过程[88, 91]。然而，^{210}Pb 具有高度不确定性，^{7}Be 的半衰期很短且没有足够的时间深入土壤，活性随着深度迅速呈指数级下降[86, 94-95]。目前，利用放射性核素技术研究土壤侵蚀的方法相对成熟，但又有其局限性，因此还需要挖掘更多合适的半衰期较长的同位素和创建更精准的估算模型[96-97]来提高土壤侵蚀的准确性。

5 人工智能（AI）与核辐射领域新发展

天然放射性核素在环境中无处不在，这些

放射性物质主要来自铀（$^{238}U/^{235}U$）和钍（^{232}Th）的衰变链[98]。植物对土壤中的放射性核素的吸收取决于植物的类型，并在不同的植物组织中分布积累，从而进入人类食物链，暴露于高水平的放射性物质会对人体产生严重影响[98-100]。因此，识别、检测土壤和植物中存在的放射性核素对环境安全评估以及人体健康影响十分重要。在过去的几十年里，AI取得了重大突破，同时也促进了放射组学等与AI相关的核辐射研究领域的蓬勃发展[101-102]。快速准确地获取检测数据以及对大量数据的分析处理能力使得AI在辐射探测领域发挥了重要作用[103]。不断发展的机器学习和图像识别技术，使得AI能够快速准确地识别辐射源并进行实时监测、定量分析环境中放射性核素的活度，还可根据隐藏在大数据中的趋势提前预测潜在的辐射风险[104-105]。

植物对养分的高效利用可以显著提高环境可持续性。多次施肥可以提高肥料利用效率，这种分次施用或及时施用方法依赖于频繁和准确地监测作物养分状况的能力，但传统监测作物养分状况的方法存在成本高、效率低等问题[106]。近红外光谱（NIRS）是一种新兴的土壤和植物养分分析技术，可以提供快速、无损的实时植物养分分析，通过保持作物养分需求和土壤供应之间的同步来积极主动地进行养分管理[106-107]。而且随着人工智能的进步和深度学习技术的发展，基于深度学习算法的NIRS检测系统应运而生。基于深度学习的NIRS分析因其高准确性、自动特征提取能力、高效处理大规模数据集和强大的非线性建模能力等优势，为该领域带来了重要的技术进步，推动了主动监测、在线分析和高效决策等多方面的发展[108-109]。与此同时，成像技术与AI技术的结合在研究植物营养物质的动态、确定全植物的运输和养分的分配等方面也发挥了重要作用。成像系统可以实时监测示踪原子的分布和活性，显示放射性示踪剂动态变化过程，获取动态的过程数据，然后通过AI技术分析影像和数据，可立即评估植物的健康状况和发育，从而能够迅速采取行动和制定具体的管理策略，还提高了检测的灵敏度和准确性[110-112]。AI技术的大数据和智能化特点，与示踪原子的高灵敏度、生物活体内物质转化动态观测有机结合，为放射性核素的创新应用奠定了基础。AI的这些优势是传统农业系统的重大转变，利用AI和现代技术有助于针对农业问题采取相应的防治措施，维护环境和生态系统的可持续发展，保障粮食安全和人类健康。

6　展望

锚定建设农业强国目标，依靠科技加快推进农业现代化，解决粮食生产稳定发展和粮食安全战略问题，利用放射性核素技术，加强辐射诱变育种、农业植物保护和水土保持已经取得了较大进展。

但是，随着新一轮科技的发展与进步，该领域面临了很多新挑战和新机遇。现代超高时间—空间分辨质谱技术的进步可以为同位素分析提供更高的精确度和灵敏度，新型同位素的开发和联合应用可为辐射研究提供更多的选择，多学科交叉融合也为核辐射研究提供了更广阔的创新与发展空间，为其技术的发展提供新的思路和方法。特别是人工智能的发展和兴起，为核技术领域带来新的发展生机，可以实现环境极端条件下辐射研究以及高通量数据深入挖掘。

因此，本研究旨在呼吁同行加强研究和技术创新合作，推动放射性核素技术在农业领域的进步，加快推进农业生产的低碳、高效和可持续发展。鉴于作者专业和关注度所限造成的不足之处也欢迎同行批评指正。

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