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前瞻观点 Viewpoint

植物进化发育生物学研究展望

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植物进化发育生物学是一门融合进化生物学、遗传学和发育生物学的交叉学科,旨在揭示植物形态、结构及其功能多样性形成的遗传机制。近年来,该领域已由传统形态学和现象学的规律描述,转向对其背后关键因子和调控路径的研究。“生命之树”重建、多维组学集成分析、精准基因组编辑及人工智能等前沿技术的快速发展,推动了植物进化发育生物学研究在宏观和微观尺度上进一步发展,并促使该领域研究范式发生根本性变革。在多学科深度交叉与大数据广泛应用的背景下,未来该领域的持续发展不仅有助于深化对植物发育及进化规律本质的理解,也将为应对全球气候变化、保护植物多样性,推动现代绿色农业转型及促进植物资源的高效利用与可持续开发等提供重要的理论支持和技术支撑,为实现人类社会的可持续发展贡献力量。

(1)植物关键性状的起源与植物进化重大事件。对植物生长发育、环境适应和生态功能起决定性作用的表型特征,通常被称为植物关键性状。在高分辨率“生命之树”框架下,精准重建植物祖先状态并追溯植物关键性状起源及其分化时间节点,是揭示植物进化机制和规律的基础。未来,相关研究将聚焦关键性状起源与重大进化事件之间的关系,围绕光合作用与绿色植物起源、抗逆性与植物登陆、生活史与世代交替进化模式、维管系统与维管植物起源、花和果实与被子植物兴起等核心科学问题开展深入探索。随着计算机模拟、古地质与气候环境重建及合成生物学等多学科技术深度融合,未来有望从多维度全面解析绿色植物起源、植物登陆及被子植物兴起等进化重大事件发生的动因、过程和机制。

(2)植物表型可塑性与快速适应性进化。表型可塑性是植物应对短期环境变化的重要策略,不仅提高了植物在变化环境中的适合度,还为遗传变异驱动的适应性进化提供了重要基础。未来研究将重点关注环境因子触发的表型可塑性机制和响应模式解析、植物环境适应能力评估及环境变化条件下物种快速适应性进化的过程和机制研究等方面。

(3)植物和其他物种的相互作用与协同进化。植物与其他物种(动物、植物和微生物等)的互作在维持生态系统稳定性方面发挥着重要作用,同时也是生物多样性和生态系统复杂性形成的重要驱动力。未来研究将从分子、细胞、个体、种群及生态系统多个层面,构建植物与微生物(共生菌与病原菌)、植物与动物(传粉者和食草动物等)之间多层次互作网络模型,解析复杂互作网络的关键节点和核心模块,揭示植物与其他物种协同进化的过程、模式及驱动力。

(4)植物多样性与新质植物资源开发利用。植物多样性是植物适应不同环境的结果,为新型高品质植物资源的筛选与开发利用提供了丰富的物质基础。面对保障国家生物安全和践行大食物观的战略需求,在全面摸清我国植物家底的前提下,未来研究将向多元化、精细化、产业化方向发展,重点聚焦于新质植物资源评价体系的建立、新质植物遗传资源的深度挖掘及新质植物性状改良与驯化等方面。

(5)人工智能与种质创制。种质创新的核心在于优异性状调控网络关键节点的精准解析与目标性状的高效定向改良。进化发育生物学与人工智能的深度耦合将推动理论研究与应用创新的双

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向突破，为植物优异种质创制及资源高效利用提供全景视角和系统解决方案。未来研究将向高精度、多维度、集成化方向发展，重点聚焦于复杂性状调控网络的精准解析、多维数据库与智能化种质创新平台的构建及面向不同应用场景的优质种质精准设计与创制等方面。

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Research Prospects in Plant Evolutionary Developmental Biology

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Plant evolutionary developmental biology（Evo-Devo）is an interdisciplinary field that integrates evolutionary biology，genetics，and developmental biology to uncover the genetic mechanisms underlying the morphological，structural，and functional diversity of plants. In recent years，the focus of plant Evo-Devo research has shifted from traditional morphological descriptions and phenomenological observations to the elucidation of key genetic factors and regulatory networks. The rapid advancement of cutting-edge technologies，including the reconstruction of the ‘Tree of Life’，integrated multi-omics approaches，precise genome editing，and artificial intelligence，have significantly propelled researches in this field at both macro- and micro-scales，fundamentally transforming its research paradigm. In the context of increasing interdisciplinary integration and the extensive application of big data，future developments in this field will not only deepen our understanding of the principles governing plant development and evolution but also provide essential theoretical frameworks and technological innovations. These insights will play a crucial role in addressing global challenges such as climate change，biodiversity conservation，the modernization of sustainable agriculture，and the efficient and sustainable utilization of plant resources，thereby supporting the broader goal of sustainable development for human society.

（1）**The origin of key innovative traits and major evolutionary events in plants**. Phenotypic traits that are critical for plant growth，development，environmental adaptation，and ecological functions are often referred to as key innovations. Within the high-resolution framework of the ‘Tree of Life’，accurately reconstructing ancestral states and tracing the origins and divergence timelines of these traits are fundamental for elucidating the mechanisms and patterns of plant evolution. Future research will emphasize investigating the links between the emergence of key innovative traits and major evolutionary transition events. Critical scientific questions include evolution of photosynthesis and the origin of green plants，the development of stress tolerance and plant terrestrialization，the evolution of life cycle and alternation of generations，the emergence of vascular systems and the origin of vascular plants，and the evolution of flowers and fruits and the rise of angiosperms. With the deep integration of multidisciplinary approaches，including computational modeling，palaeogeological and paleoenvironmental reconstructions，and synthetic biology，future studies are expected to multidimensional and comprehensively illuminate the driving forces，processes，and mechanisms behind major evolutionary milestones such as the origin of green plants，the colonization of land，and the rise and rapid radiation of angiosperms.

（2）**Phenotypic plasticity and rapid adaptive evolution in plants**. Phenotypic plasticity is a vital strategy that enables plants to respond to short-term environmental fluctuations. It not only enhances the fitness of plants under changing conditions but also provide a critical basis for rapid adaptive evolution driven by genetic variations. Future researches will focus on elucidating the mechanisms and dynamic re-

ponse patterns underlying environmentally induced phenotypic plasticity, evaluating the adaptive capacity of plants to diverse environmental stresses, and exploring the processes and molecular mechanisms that underpin rapid adaptive evolution in species shifting environmental conditions.

(3) **Interactions and co-evolution between plants and other species**. Interactions between plants and other organisms, including animals, other plants, and microorganisms, are key drivers of biodiversity, ecological complexity, and ecosystem stability. Future studies will aim to construct comprehensive, multi-layered interaction network models that describe plant-microbe (including symbiots and pathogens) and plant-animal (such as pollinators and herbivores) relationships across molecular, cellular, individual, population, and ecosystem scales. Such research will help identify critical nodes and core modules in these complex networks, providing insights into the processes, patterns, and driving forces of co-evolution between plants and associated species.

(4) **Plant diversity and the utilization of novel germplasms**. The rich diversity of plants, shaped by adaptation to heterogeneous environments, offers a vast reservoir for identifying and developing new high-quality plant resources. In response to strategic needs such as safeguarding national biosecurity and advancing the 'Great Food View' strategy. Future research should build on comprehensive surveys of plant resources to promote diversification, refinement, and industrialization. Key research directions will include establishing robust evaluation systems for novel plant resources, mining and characterizing new genetic materials, and accelerating the improvement and domestication of traits with desirable agricultural, ecological, or industrial value.

(5) **Artificial intelligence and germplasm innovation**. The core of germplasm innovation is the precise identification of key regulatory nodes governing superior traits and the efficiently targeted enhancement of these traits. The integration of plant evolutionary developmental biology with artificial intelligence will drive transformative advances in both fundamental research and applied innovation, providing comprehensive insights and systematic solutions for creating superior plant germplasms and enabling efficient resource utilization. Future efforts will emphasize the high-precision, multidimension, and integration, focusing on the in-depth analysis of complex trait regulatory networks, the development of multidimensional databases and intelligent germplasm innovation platforms, and the precise design and creation of high-quality germplasms tailored to diverse application scenarios.