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Revolutionizing Plant Taxonomy through Integrative Approaches and Artificial Intelligence - A Review

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Abstract

Plant taxonomy, the foundation of botanical science, is entering a transformative era driven by the integration of artificial intelligence (AI) and multidisciplinary data. Traditional taxonomy has relied heavily on morphological traits, but the complexity of plant diversity and cryptic species often challenges human-based identification. Integrative taxonomy, which combines morphological, molecular, ecological, and geographical data, provides a more holistic framework for species delimitation. However, handling and interpreting such heterogeneous data demand computational methods capable of recognizing complex patterns and relationships.

Here, we present an overview of how AI particularly machine learning and deep learning can revolutionize plant taxonomy by automating data analysis, detecting hidden diversity, and accelerating species identification. We highlight the integration of image-based recognition of plant organs, DNA barcoding classification, and ecological niche modelling through AI algorithms. Additionally, we discuss recent advances in multimodal data fusion that enable the synthesis of molecular and phenotypic datasets for more robust taxonomic decisions. The study emphasizes the potential of AI to enhance reproducibility, reduce human bias, and enable rapid biodiversity assessment in the face of global environmental change.

We conclude that the synergy between integrative taxonomy and artificial intelligence represents a paradigm shift in plant systematics, paving the way for a new era of automated, data-driven taxonomy and biodiversity discovery.

Keywords: Integrative taxonomy, plant systematics, artificial intelligence, machine learning, DNA barcoding, deep learning, biodiversity.

1. Introduction

[1]Plant taxonomy forms the cornerstone of botanical science, providing the framework for naming, describing, and classifying plant diversity. Traditional taxonomy, grounded in morphological observation and expert judgment, has served science for centuries but now faces challenges from rapid biodiversity loss, climate change, and the explosion of digital data. The number of undescribed plant species remains high, while taxonomic expertise continues to decline (Heberling et al., 2019). Integrative and AI-assisted approaches are emerging as transformative tools that can modernize this discipline by accelerating species discovery and improving the accuracy of classifications.

[2]**Integrative taxonomy**—which combines multiple evidence sources such as morphology, molecular data, ecology, and chemistry—represents a paradigm shift toward more robust species delimitation (Maltsev, 2023). This holistic approach reduces subjectivity and allows reconciliation between traditional and molecular evidence. Simultaneously, **artificial intelligence (AI)** and **machine learning (ML)** offer computational solutions for handling the massive influx of data from digitized herbarium specimens, DNA sequencing, and remote sensing (Truong et al., 2024). AI-driven image recognition systems now identify species from leaf or flower images with expert-level accuracy, while deep learning architectures facilitate high-throughput phenotyping and trait extraction (Barhate et al., 2024).

[3]Integrating AI into plant taxonomy is not merely a technical upgrade—it is a conceptual revolution. Machine learning models trained on herbarium images, genomic data, and field photographs can detect cryptic species, analyze intraspecific variation, and even reconstruct phylogenetic relationships. Such methods democratize taxonomy by enabling non-specialists and citizen scientists to participate in species identification through platforms like Pl@ntNet and iNaturalist (Pearson et al., 2020).

[4]However, the transition is not without challenges. Data quality, algorithmic bias, taxonomic uncertainty, and ethical considerations must be addressed to ensure responsible and reproducible AI applications (Sandall et al., 2023). This review synthesizes current knowledge on integrative taxonomy and AI in plant classification, emphasizing methodological advances, applications, challenges, and future directions.

2. Evolution of Plant Taxonomy and the Rise of Integrative Approaches

[5]Early plant taxonomy relied primarily on morphological traits—leaf shape, floral structures, and reproductive organs—to delineate species. Although morphology remains foundational, it is increasingly supplemented by molecular and ecological data to overcome its limitations in cases of convergent evolution or phenotypic plasticity (Lettsiou, 2024).

[6]**Molecular systematics** revolutionized taxonomy during the late 20th century. DNA barcoding using markers such as *rbcL*, *matK*, and ITS provided standardized genetic references for plant identification (Kress & Erickson, 2018). Yet, single-locus barcoding often fails in groups with hybridization or incomplete lineage sorting, leading to the adoption of **phylogenomics**, which uses hundreds or thousands of loci to infer relationships (Wang et al., 2023).

[7]**Integrative taxonomy** emerged to address inconsistencies between datasets. It advocates combining morphological, molecular, ecological, and chemical evidence for holistic species delimitation. Recent work using *Platanthera* orchids and *Carex* sedges illustrates how genomic data corroborate morphological distinctions, resolving taxonomic ambiguity (Maltsev, 2023).

[8]Beyond DNA, **chemotaxonomy and metabolomics** are increasingly used to differentiate species based on their unique biochemical fingerprints (Marín-Rodulfo et al., 2024). This approach is particularly effective for cryptic or closely related taxa. **Geometric morphometrics**, enabled by digital imaging, quantifies subtle shape variations that may be imperceptible to the human eye (Pacal et al., 2024). Together, these methods reflect a convergence of disciplines that make taxonomy more quantitative, reproducible, and scalable.

[1]The digitization of herbaria and the emergence of global data repositories like GBIF and iDigBio have amplified the power of integrative taxonomy. Millions of specimens are now available as high-resolution images with georeferenced metadata, enabling cross-institutional analyses and feeding data-hungry AI models (Heberling et al., 2019).

3. Artificial Intelligence and Machine Learning in Plant Taxonomy

AI has redefined how species are identified, classified, and analyzed. **Machine learning**, particularly **deep learning**, can automatically detect features, classify species, and analyze large-scale datasets derived from digitized specimens, genomic sequences, and remote sensing.

3.1 Image-Based Identification

[3]Deep convolutional neural networks (CNNs) have achieved remarkable performance in classifying plant species from leaf, flower, and herbarium images (Truong et al., 2024). Architectures like ResNet, EfficientNet, and Vision Transformers have achieved over 95% accuracy in certain datasets, outperforming human experts in some tests. The *Pl@ntNet* and *iNaturalist* platforms are exemplary applications, leveraging crowd-sourced images to train and improve models (Pearson et al., 2020).

3.2 Trait Extraction and Phenology

[1]AI automates the extraction of morphological traits (e.g., leaf area, venation, floral morphology) and phenological data (flowering and fruiting times) from herbarium images (Barhate et al., 2024). These data can be integrated with climate and genomic data to study plant responses to environmental change (Heberling et al., 2019).

3.3 Genomic and Phylogenetic Integration

[6]Machine learning is increasingly applied to phylogenetic inference, clustering, and unsupervised species delimitation using genomic datasets. Integrative pipelines now combine genetic, morphological, and image data, offering a more holistic view of biodiversity (Wang et al., 2023).

3.4 Remote Sensing and Biodiversity Mapping

[8]AI-driven remote sensing supports species mapping and ecosystem monitoring. Hyperspectral imagery, drones, and satellite data enable landscape-scale classification of plant species and functional traits, providing critical insights for conservation (Pacal et al., 2024).

3.5 Challenges and Limitations

[4]AI models require massive, balanced datasets and can be biased by uneven taxonomic sampling. Data noise, image variability, and incomplete metadata also reduce performance. Moreover, AI models often lack interpretability, which complicates their integration into formal taxonomic workflows (Sandall et al., 2023).

4. Risks, Ethical Considerations, and Limitations

[4]Despite AI's promise, challenges persist. Data bias remains a fundamental issue—models trained on limited geographic regions often fail to generalize globally (Truong et al., 2024). Many plant groups are underrepresented in digital datasets, creating a skewed taxonomic picture (Sandall et al., 2023).

[7]Ethical concerns involve data ownership, privacy, and intellectual property—especially for genomic resources from biodiversity-rich regions (Heberling et al., 2019). Algorithmic transparency and reproducibility are also crucial to maintain scientific credibility. Furthermore, overreliance on automated systems may erode taxonomic expertise and critical evaluation (Maltsev, 2023).

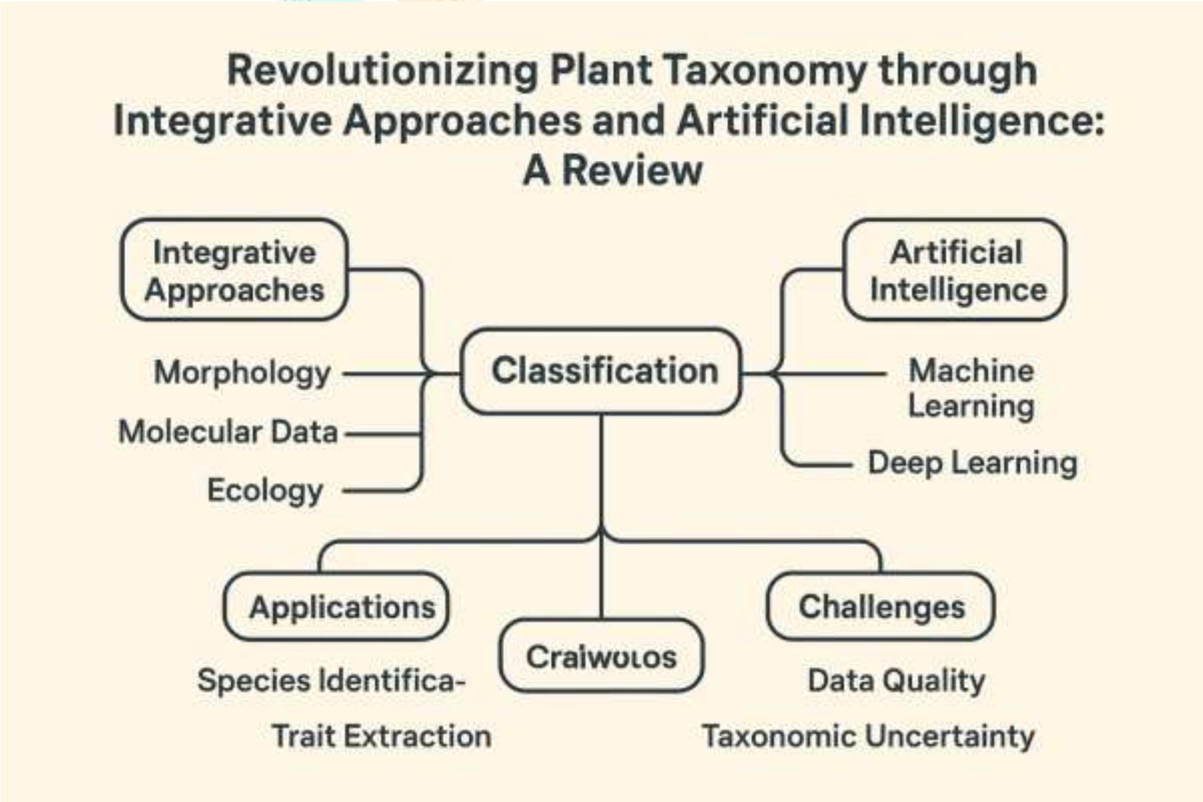
[2]AI models should therefore be developed as **assistive, not replacement, tools** for human taxonomists. Human-in-the-loop frameworks where experts validate and refine AI outputs represent a responsible pathway forward (Barhate et al., 2024).

5. Future Directions and Research Roadmap

[8]The next decade will likely see a shift from single-modality models to **multimodal AI**, integrating genomic, morphological, ecological, and spectral data for comprehensive taxonomic analysis. **Explainable AI (XAI)** can improve interpretability by visualizing which features drive model predictions (Pacal et al., 2024).

[9]Advances in **high-throughput sequencing**, **cloud-based data sharing**, and **open-access repositories** will enhance reproducibility and collaboration (Marín-Rodulfo et al., 2024). [4]Future frameworks should also emphasize **FAIR data principles** (Findable, Accessible, Interoperable, Reusable) and **capacity building** in underrepresented regions to ensure global participation in AI-enabled taxonomy (Sandall et al., 2023).

Integrating AI into integrative taxonomy will not replace classical expertise but rather augment it—creating a synergistic relationship between computational precision and biological insight.



6. Conclusion

Integrative approaches and AI together mark a turning point in plant taxonomy. From molecular barcoding and chemotaxonomy to deep learning-based image recognition, the tools now available enable faster, more objective, and data-driven classification. Yet, technology must serve taxonomy not replace it. Responsible AI use requires ethical vigilance, expert oversight, and global collaboration.

The convergence of integrative methods and artificial intelligence is not just revolutionizing taxonomy it is redefining how we perceive and preserve plant diversity in a rapidly changing world.

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