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AI-Powered Monitoring of Medicinal Plant Resources to Advance Precision Healthcare and Sustainable Conservation: A Review of Developments to 2020

Siddhartha Mehrotra[1], Dr. Gauri Saxena[2*]

[1*]Research Scholar, Department of Botany, University of Lucknow, siddharthamehrotra10@gmail.com, 0009-0009-1515-4495
[2]Professor, Department of Botany, University of Lucknow, gaurigupta72@yahoo.com, 0000-0003-2235-2755

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Abstract
Medicinal plants have long formed the backbone of traditional healthcare systems and continue to supply leads for modern pharmaceuticals. Rising demand, combined with habitat degradation, overharvesting and climate pressures, has placed many species under severe threat. By 2020, machine learning, remote sensing and sensor-based monitoring had begun to offer practical tools for mapping distributions, identifying species from images, assessing habitat suitability and supporting quality control of plant material. This review examines the literature published up to 2020 on these approaches. It covers classical and early deep-learning methods for leaf-image classification, maximum-entropy and related species-distribution models, hyperspectral and spectroscopic quality assessment, and the first applications of environmental sensors in cultivation settings. Emphasis is placed on how these technologies can simultaneously reduce pressure on wild populations and improve the consistency of raw materials required for evidence-based herbal medicine. Remaining limitations in data availability, model transferability and field deployment are discussed, together with priorities that were already evident by the end of the decade.

Keywords: Medicinal plants, Machine learning, Remote sensing, Leaf-image classification, Species-distribution models, Hyperspectral quality assessment, Environmental sensors

Introduction

An estimated four-fifths of people in many developing regions still rely primarily on plant-based traditional medicine. At the same time, natural products or their derivatives account for a substantial share of approved drugs. Global trade in medicinal and aromatic plants expanded rapidly in the decades leading up to 2020, yet wild populations of numerous high-value species declined under commercial collection, agricultural expansion and changing climate regimes. Conventional monitoring—expert field surveys, morphological keys and sporadic chemical sampling—remained slow, spatially incomplete and heavily dependent on scarce taxonomic expertise.By the late 2010s a range of computational and sensing technologies had matured sufficiently to address some of these constraints. Image-based machine-learning classifiers could distinguish species from leaf photographs with useful accuracy. Species-distribution models, particularly MaxEnt, projected current and future habitat suitability from occurrence records and bioclimatic layers. Hyperspectral imaging and chemometric methods offered non-destructive routes to authentication and quality grading. Early sensor networks and controlled-environment systems began to support more consistent cultivation. Collectively these tools pointed toward a dual benefit: better information for conservation planning and more reliable supplies of standardised plant material for healthcare applications.This review synthesises peer-reviewed work published up to 2020. It is organised around the principal technological strands, their demonstrated applications to medicinal plants, performance characteristics reported at the time, and the practical obstacles that remained unresolved.

2. Image-Based Identification of Medicinal Plants :

Accurate species identification underpins both conservation inventories and the prevention of adulteration in herbal supply chains. Traditional morphological keys require trained botanists and are difficult to apply at scale. From the mid-2000s onward, researchers therefore explored automated classification of leaf images.Early systems extracted hand-crafted features—shape descriptors (aspect ratio, rectangularity, circularity), vein patterns, texture statistics (grey-level co-occurrence matrices, local binary patterns) and colour histograms—then fed them to classical classifiers such as support-vector machines, k-nearest neighbours, random forests, multilayer perceptrons and decision trees. Public leaf datasets such as Flavia and Swedish Leaf provided benchmarks, although few contained large numbers of medicinally important taxa. Reported accuracies on these general datasets frequently exceeded 90 percent when multiple feature types were combined.

A comprehensive review published in 2020 surveyed the machine-learning literature specifically for medicinal-plant recognition. The authors organised studies according to the dominant feature set employed (shape, vein, texture or combinations) and noted that hybrid feature vectors generally outperformed single-feature approaches. They also catalogued the limited number of publicly available medicinal-plant image collections and highlighted the scarcity of images captured under realistic field conditions. Performance of the classical algorithms was shown to degrade when leaf orientation, illumination or background clutter varied substantially.

Toward the end of the decade convolutional neural networks began to appear. Transfer learning from networks pre-trained on ImageNet (AlexNet, VGG, early ResNet variants) allowed useful results even with modest numbers of medicinal-plant images. Several 2018–2020 studies reported classification accuracies above 95 percent on small, laboratory-collected leaf sets of ten to thirty species. These early deep-learning results were encouraging, yet most models still operated on isolated leaves against uniform backgrounds and had not been stress-tested on whole-plant photographs or images taken in the wild.

Citizen-science applications and mobile prototypes were also emerging. Although large-scale public systems capable of recognising tens of thousands of species were still under development, the principle that smartphone cameras plus trained classifiers could assist non-experts was already established. For conservation purposes the same technology offered a route to rapid field inventories; for healthcare it promised a first-line check against misidentification of raw materials.

3. Species-Distribution Modelling and Habitat Mapping:

Knowing where medicinal plants currently occur and where they are likely to persist under future climates is essential for both in-situ conservation and the selection of cultivation sites. Species-distribution models (SDMs) relate occurrence records to environmental predictors and project suitability across geographic space.Maximum entropy modelling (MaxEnt) became the dominant algorithm for medicinal-plant studies because it performs well with presence-only data and modest sample sizes. By 2013 MaxEnt had already been applied to Justicia adhatoda in the Indian Himalayan foothills, combining bioclimatic variables, topography and land-cover layers derived from satellite imagery. The model achieved an area-under-curve value above 0.9 and identified priority zones for restoration. Similar workflows were later used for numerous Chinese, Egyptian and and Himalayan taxa.

A 2017 study of Egyptian medicinal plants employed MaxEnt with 23 environmental predictors, including WorldClim bioclimatic variables and multi-year NDVI, to map current richness and to project changes under two IPCC scenarios to 2080. The authors identified present-day hotspots and showed that many species were likely to experience range contractions or shifts. Ensemble and MaxEnt alone produced broadly similar suitability maps, suggesting that a single well-tuned algorithm could often suffice.

Remote-sensing data entered these models primarily as static land-cover or vegetation-index layers. UAV platforms capable of centimetre-resolution imagery were still largely experimental for medicinal-plant surveys by 2020, although their potential for fine-scale abundance estimation was recognised. Overall, the SDM literature up to 2020 demonstrated that habitat-suitability maps could guide the designation of collection zones, the location of cultivation trials and the prioritisation of populations for genetic conservation. The principal weaknesses remained the sparse and spatially biased nature of occurrence records for many medicinal taxa and the limited incorporation of soil chemistry or biotic interactions.

4. Spectroscopic and Hyperspectral Methods for Quality Assessment :

Consistency of bioactive constituents is critical if herbal preparations are to meet pharmacopoeial standards and support reproducible clinical outcomes. Conventional chromatographic assays are accurate but destructive, slow and laboratory-bound. Near-infrared, mid-infrared and hyperspectral imaging combined with multivariate calibration offered faster, non-destructive alternatives.

By 2020 a substantial body of work had shown that partial least-squares regression, support-vector machines and early neural-network models could predict concentrations of marker compounds from spectral data. Hyperspectral imaging added spatial resolution, allowing simultaneous examination of multiple samples or mapping of chemical variation within a single plant organ. Feasibility studies on Cannabis demonstrated that selected near-infrared bands plus soft independent modelling of class analogy could distinguish species or chemotypes with high sensitivity and specificity. Parallel efforts on traditional Chinese medicinal materials used similar pipelines for authentication and detection of adulterants.

These methods directly served precision-healthcare goals by enabling rapid screening of incoming raw materials and by reducing the risk that sub-standard or substituted material would enter manufacturing. From a conservation standpoint, reliable quality assessment of cultivated material reduced the economic incentive for continued wild harvesting of high-potency populations. Limitations included the need for large, well-characterised calibration sets, sensitivity to particle size and moisture content, and the still-modest number of portable instruments suitable for field or farm-gate use.

5. Sensor Networks and Early Precision Cultivation :
Although full-scale IoT platforms for medicinal plants remained uncommon by 2020, the underlying sensor technologies were already being applied. Soil-moisture, temperature, humidity and light sensors linked to simple data loggers or early wireless nodes allowed continuous monitoring of cultivation environments. In greenhouse settings these data supported more precise irrigation and climate control, which in turn improved biomass yield and, in some trials, secondary-metabolite concentrations.
A few systems incorporated basic machine-learning components—for example, clustering algorithms to remove noisy sensor readings or neural networks to evaluate overall soil suitability. Controlled-environment experiments also began to explore the effects of specific light spectra on the accumulation of pharmaceutically relevant compounds. While most published examples still focused on a handful of high-value herbs, the principle that continuous environmental monitoring could stabilise both yield and quality was clearly established. Such stabilisation is a prerequisite for shifting production from unpredictable wild collection to managed cultivation, thereby easing pressure on natural populations.

6. Linking Monitoring Technologies to Conservation and Healthcare Outcomes :
The technologies reviewed above converge on two practical outcomes. First, improved spatial intelligence—species maps, habitat-suitability surfaces and population estimates—supports the design of sustainable harvest quotas, the identification of genetic reserves and the selection of sites for commercial cultivation. Second, rapid identification and quality-assessment tools reduce adulteration and variability in the supply chain, increasing the likelihood that herbal products can meet the reproducibility standards expected in contemporary healthcare.
By 2020 these linkages were still largely conceptual or demonstrated only at pilot scale. Nevertheless, case studies already illustrated the pathway: MaxEnt maps guiding the location of cultivation trials; leaf-image classifiers assisting community collectors; and spectroscopic screening rejecting sub-standard batches before they entered manufacturing. The dual benefit—conservation through reduced wild harvesting and healthcare through more consistent raw materials—was therefore recognisable even if not yet widely realised.

7. Limitations Evident by 2020 :
Several constraints appeared repeatedly across the literature. Image-classification models trained on laboratory leaves generalised poorly to field photographs. Occurrence data for many medicinal species remained sparse, geographically biased toward accessible regions, and rarely accompanied by abundance or demographic information. Spectroscopic calibrations were often instrument- or laboratory-specific. Sensor networks faced power, connectivity and cost barriers in remote cultivation areas. Finally, few studies integrated ecological, agronomic and chemical data into a single decision-support framework. These gaps limited immediate operational uptake and pointed to clear priorities for subsequent research.

Conclusions : Work published up to 2020 demonstrated that machine learning, species-distribution modelling, spectroscopic analysis and environmental sensing could each contribute useful information for the monitoring of medicinal plant resources. Image-based classifiers and MaxEnt habitat maps improved the speed and geographic coverage of inventories. Non-destructive quality methods supported authentication and standardisation. Early sensor systems pointed toward more reliable cultivation. Taken together, these advances offered a technical foundation for reconciling the growing demand for plant-based healthcare products with the need to conserve wild populations. Realising that potential required larger, more representative datasets, models robust to real-world variation, and closer collaboration among ecologists, agronomists, chemists and healthcare regulators—tasks that were already clearly identified by the end of the decade.

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12. Classical texture and shape feature papers for plant leaves (e.g., using GLCM, LBP, 2005–2018).
13. Random-forest and SVM applications to multi-feature leaf classification (various, pre-2020).
14. NDVI and satellite-derived predictors in medicinal-plant SDMs (Egyptian and Asian case studies, 2015–2020).
15. Early greenhouse sensor and climate-control trials for high-value herbs (2015–2020).
16. Chemometric authentication of traditional Chinese medicinal materials by infrared spectroscopy (multiple reviews and primary studies to 2020).
17. Presence-only modelling best-practice discussions (Phillips, Elith and co-authors).
18. Public leaf-image database descriptions and benchmarking studies (Flavia, Swedish Leaf and early medicinal subsets).
19. Studies linking cultivation environment to secondary-metabolite variation (pre-2020 controlled-environment work).
20. Reviews of remote-sensing applications in plant ecology and conservation up to 2020.