Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Non-Destructive Assessment of Heritage Tree Structural Integrity Using Electrical Resistance Tomography for Conservation and Urban Tree Risk Management

Baragur N. Divakara[1]

bndsira@gmail.com

[1]ICFRE–Institute of Wood Science and Technology

C. Buvaneswaran[2]

ICFRE – Institute of Forest Genetics and Tree Breeding

Research Article

Keywords: Electrical Resistance Tomography, Heritage trees, Non-destructive testing, Internal structural integrity, Heartwood, Urban forestry, Tree risk assessment, Conservation management

Posted Date: September 15th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10720380/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Heritage trees constitute irreplaceable ecological, historical, and cultural assets in urban landscapes, yet their long-term conservation requires accurate evaluation of internal structural integrity, which cannot be reliably assessed through visual inspection alone. Hidden defects such as internal decay, hollowness, moisture accumulation, and poorly developed heartwood may substantially reduce mechanical stability while remaining externally undetectable. The present study evaluated the internal structural condition of fifteen candidate heritage trees representing diverse tropical species in Chennai, India, using Electrical Resistance Tomography (ERT) as a non-destructive diagnostic technique. ERT measurements were performed at breast height (1.37 m) using the PiCUS TreeTronic system to generate two-dimensional cross-sectional tomograms depicting spatial variations in electrical resistivity associated with wood moisture content, heartwood development, and structural integrity. The tomograms were interpreted based on radial resistivity distribution, heartwood continuity, moisture heterogeneity, presence of low-resistance anomalies, and evidence of hollowness or internal decay. Based on these characteristics, trees were classified into structural health categories to determine their suitability for heritage designation. Most evaluated trees exhibited distinct radial differentiation characterized by well-developed high-resistance heartwood surrounded by low-resistance physiologically active sapwood, indicating sound internal architecture with no evidence of advanced decay or extensive hollowness. Approximately 80% of the assessed trees possessed structurally competent heartwood and were considered suitable for heritage tree designation, whereas a smaller proportion exhibited diffuse low-resistance zones associated with elevated internal moisture and limited heartwood development, warranting periodic monitoring and confirmatory assessment. None of the investigated trees exhibited catastrophic internal structural failure or complete stem hollowness. The findings demonstrate that Electrical Resistance Tomography provides a rapid, objective, and reliable non-destructive approach for evaluating hidden internal defects and structural stability of heritage trees. Integrating ERT with conventional visual tree assessment can substantially improve heritage tree selection, urban tree risk assessment, and evidence-based conservation planning while minimizing unnecessary removal of historically and ecologically valuable trees. The study establishes a scientific framework for incorporating advanced non-destructive technologies into heritage tree conservation and urban forest management.

1. Introduction

Heritage trees are living monuments of exceptional ecological, cultural, historical, aesthetic, and scientific significance. Many survive for centuries and serve as repositories of biodiversity, genetic resources, carbon, and ecological memory. Large, old trees provide habitat for numerous organisms, support complex ecological interactions, and contribute to long-term ecosystem functioning. Some trees are exceptional in their longevity, such as the 1,500-year-old Big Cypress on Cat Island, Louisiana. They may also serve as landmarks and repositories of cultural memory through their associations with historical events, religious traditions, traditional practices, and local communities. In urban landscapes, heritage trees provide important ecosystem services, including carbon sequestration, climate regulation,

air purification, storm-water mitigation, habitat provision, and enhancement of human well-being. Therefore, their identification, scientific assessment, documentation, and long-term conservation are essential for safeguarding these irreplaceable natural and cultural assets (Jim, 2004; Lindenmayer et al., 2012; Roman et al., 2018).

Rapid urbanization, infrastructure expansion, environmental pollution, climate change, and increasing anthropogenic disturbances have significantly increased the vulnerability of mature urban trees worldwide. Ageing processes, repeated mechanical injuries, fungal infections, insect attacks, root disturbances, soil compaction, drought stress, and extreme weather events progressively compromise the internal structural integrity of trees. While external symptoms such as stem cavities, fungal fruiting bodies, bark cracks, crown dieback, or branch failure may indicate advanced deterioration, many structurally significant defects develop internally and remain invisible until catastrophic failure occurs. Hidden decay and hollowness substantially reduce the load-bearing capacity of stems and branches, posing considerable risks to public safety, infrastructure, and property, particularly in densely populated urban environments. Consequently, reliable evaluation of internal tree condition has become a critical component of urban forestry, arboriculture, and heritage tree conservation (Mattheck and Breloer 1994; Smiley et al. 2017; James et al. 2018).

Traditionally, tree health assessments have relied primarily on Visual Tree Assessment (VTA), which evaluates external morphological characteristics, crown architecture, stem defects, bark condition, root flare, and signs of biological deterioration. Although VTA remains the first step in tree risk assessment, its diagnostic capability is inherently limited because external symptoms frequently do not correspond to the actual internal condition of the wood. Trees often compartmentalize decay effectively, allowing substantial internal deterioration to occur without obvious external manifestations. Conversely, external wounds may not necessarily indicate severe structural weakness. Therefore, reliance solely on visual inspection may lead either to unnecessary removal of structurally sound heritage trees or to failure in identifying hazardous trees with hidden internal defects (Mattheck and Breloer 1994; Smiley et al. 2017).

To overcome these limitations, several non-destructive evaluation (NDE) techniques have been developed for investigating internal wood properties without causing significant injury to the tree. These include stress-wave tomography, acoustic tomography, sonic tomography, ground-penetrating radar, micro-drilling resistance, X-ray computed tomography, magnetic resonance imaging, and Electrical Resistance Tomography (ERT). Among these methods, ERT has emerged as one of the most promising diagnostic tools because it provides rapid, portable, non-invasive, and repeatable assessment of internal stem condition under field conditions. Unlike invasive methods such as increment boring or destructive sampling, ERT preserves the structural integrity of valuable trees while providing detailed information on the spatial distribution of internal wood properties (Nicolotti et al. 2003; Bieker and Rust 2010a; Deflorio et al. 2010).

Electrical Resistance Tomography is based on the principle that the electrical resistivity of wood varies according to its moisture content, density, anatomical structure, ionic concentration, and degree of

biological degradation. In living trees, moisture-rich sapwood generally exhibits relatively low electrical resistance because dissolved ions facilitate electrical conductivity, whereas dry, compact heartwood usually possesses higher resistance owing to reduced moisture content and lower ionic mobility. Decayed or moisture-saturated tissues frequently display markedly reduced resistivity compared with healthy wood, enabling the detection of hidden defects that cannot be observed externally. By injecting low electrical currents through multiple electrodes positioned around the stem circumference and measuring voltage differences between electrode pairs, ERT reconstructs two-dimensional tomographic images depicting the internal distribution of electrical resistivity. These tomograms allow identification of heartwood development, moisture gradients, decay pockets, cavities, and structural discontinuities, thereby providing valuable information on the internal health of standing trees (Bieker and Rust 2010b; Deflorio et al. 2010; Brazee et al. 2011).

Over the past two decades, ERT has been successfully applied for detecting internal decay in numerous temperate tree species, evaluating moisture dynamics, identifying fungal infections, monitoring heartwood formation, and assessing structural stability in urban trees. Several studies have demonstrated strong relationships between electrical resistivity patterns and wood condition, highlighting the potential of ERT for improving tree risk assessment and conservation decisions. Nevertheless, the interpretation of ERT images remains species-dependent because wood anatomy, heartwood chemistry, moisture distribution, and physiological characteristics differ considerably among taxa. Consequently, calibration and validation under local environmental conditions are essential for reliable interpretation of tomographic images (Bieker and Rust 2010b; Deflorio et al. 2010; Brazee et al. 2011).

Despite increasing global interest in non-destructive tree diagnostics, relatively few studies have examined the application of Electrical Resistance Tomography to tropical heritage tree species, particularly under Indian environmental conditions. Most available investigations have focused on temperate urban trees or commercially important timber species, whereas scientific information regarding internal structural integrity of large tropical heritage trees remains extremely limited. Furthermore, existing heritage tree selection programmes frequently rely on external characteristics such as age, girth, historical importance, aesthetic value, and visual health, with limited consideration of concealed internal defects that may significantly influence long-term structural stability and public safety. The absence of objective internal assessment criteria may result in inappropriate conservation decisions and increased management risks.

The present investigation addresses this important knowledge gap by employing Electrical Resistance Tomography to evaluate the internal structural integrity of candidate heritage trees representing diverse tropical species in Chennai, India. The study aims to establish scientifically robust criteria for interpreting resistivity patterns associated with heartwood development, moisture distribution, internal heterogeneity, and potential structural defects, thereby supporting evidence-based heritage tree selection and conservation. By integrating non-destructive diagnostic technology with conventional arboricultural assessment, the study contributes to the development of more objective protocols for evaluating

heritage tree health, minimizing unnecessary tree removal, prioritizing conservation efforts, and enhancing urban tree risk management.

Objectives

The specific objectives of the present study were to:

1. Evaluate the internal structural integrity of candidate heritage trees using Electrical Resistance Tomography.
2. Characterize internal resistivity patterns associated with heartwood development, sapwood distribution, and moisture heterogeneity.
3. Detect hidden internal anomalies, including moisture-rich zones, structural discontinuities, and potential decay, that are not apparent through external visual assessment.
4. Classify candidate heritage trees according to their internal structural health and suitability for heritage designation.
5. Demonstrate the applicability of Electrical Resistance Tomography as a scientific decision-support tool for heritage tree conservation and urban tree risk assessment.

Hypothesis

This study was based on the hypothesis that candidate heritage trees exhibiting continuous high-resistance heartwood zones with distinct radial differentiation possess superior internal structural integrity and mechanical stability, whereas trees dominated by diffuse low-resistance regions indicate elevated internal moisture, limited heartwood development, or incipient structural deterioration, thereby requiring closer monitoring and management interventions. This investigation provides one of the first comprehensive evaluations of tropical heritage trees using Electrical Resistance Tomography in India and establishes a scientific framework for incorporating non-destructive internal structural assessment into heritage tree conservation, urban forestry, and evidence-based arboricultural management.

2. Material and methods

2.1 Study Area

The present investigation was conducted on selected candidate heritage trees located in Chennai, Tamil Nadu, India, one of the oldest metropolitan cities on the south-eastern coast of the Indian peninsula. Chennai (13°05' N, 80°16' E) experiences a tropical wet-and-dry climate (Aw) according to the Köppen climatic classification, characterized by high temperatures and pronounced seasonal rainfall. The city has an average annual rainfall of approximately 1,200–1,400 mm, of which nearly 60% is received during the northeast monsoon (October–December). Mean annual temperature ranges from 24 to 38°C, while relative humidity generally varies between 65 and 85%. The soils are predominantly sandy loam to clay loam with variable drainage conditions depending on location.

The trees investigated in this study were distributed across different institutional campuses, public parks, historical premises, and urban green spaces within Chennai. These trees represent valuable biological and cultural assets owing to their exceptional size, age, historical importance, ecological significance, and landscape value. The study formed part of a scientific initiative aimed at identifying suitable candidates for inclusion under the Heritage Tree Programme through objective evaluation of their internal structural condition. Conventional field observations were integrated with Electrical Resistance Tomography (ERT) to assess hidden internal defects that cannot be detected through external visual examination alone (Divakara and Chaithra, 2022; Divakara and Singh, 2025).

2.2 Selection of Candidate Heritage Trees

A total of 52 mature trees belonging to 28 tropical tree species were selected for detailed investigation based on preliminary field surveys and recommendations from forestry experts. All heritage tree species included in the study were identified by S. P. Subramani, Taxonomist. The selected species included *Adansonia digitata* (4 no.), *Anogeissus acuminata* (2 no.), Anogeissus acuminate (2 no.), *Azadirachta indica* (4 no.), *Barringtonia acutangula* (3 no.), *Bombax malabaricum* (1 no.), *Butea monosperma* (2 no.), *Diospyros malabarica* (2 no.), *Dolichandrone falcate* (1 no.), *Elaeodendron glaucum* (1 no.), *Guaiacum officinale* (1 no.), *Hardwickia binate* (1 no.), *Hura creptians* (1 no.), *Lannea coromandelica* (1 no.), *Madhuca longifolia* (2 no.), *Mimusops elengi* (1 no.), *Morinda pubescens* (1 no.), *Neolamarckia kadamba* (1 no.), *Prosopis cineraria* (3 no.), *Putranjiva roxburghii* (3 no.), *Schleisera oleosa* (1 no.), *Sterculia foetida* (1 no.), *Strychnos nux-vomica* (1 no.), *Swietenia mahagoni* (6 no.), *Syzygium cumini* (2 no.), *Tamarindus indica* (2 no.), *Terminalia arjuna* (4 no.) and *Terminalia bellerica* (1 no.). The uploaded report documents these individual assessments and their ERT interpretations.

Trees were selected using the following criteria:

- Mature individuals possessing large stem diameter and well-developed crowns.
- Historical, cultural, ecological, or landscape significance.
- Good external accessibility for ERT measurements.
- Absence of severe external injuries preventing electrode installation.
- Representation of different botanical families and wood anatomical characteristics.
- Candidate status for heritage tree recognition.

Each selected tree was assigned a unique identification number for subsequent analysis and documentation.

2.3 Field Measurements

Prior to ERT assessment, each tree was subjected to a comprehensive field inspection following standard arboricultural procedures. The following parameters were recorded: (i) Botanical name (ii) Tree identification number, (iii) Geographic location (GPS), (iv) Diameter at breast height (DBH), (v) Stem circumference, (vi) Estimated tree height, (vii) Crown spread, (h) General crown condition, (viii) Presence

of external defects, (ix) Bark characteristics, (x) Presence of fungal fruiting bodies, (xi) Stem wounds or cavities (xii) Root exposure (xiii) Lean angle and (xiv) Mechanical injuries.

Diameter at breast height was measured at 1.37 m above ground level using a diameter tape. Tree height was estimated using a laser hypsometer. External tree condition was evaluated according to internationally accepted Visual Tree Assessment (VTA) principles. The field observations served as supporting information for interpreting the tomographic images and identifying relationships between external symptoms and internal structural condition.

2.4 Electrical Resistance Tomography

Internal structural integrity was assessed using the PiCUS TreeTronic Electrical Resistance Tomography (ERT) system (Argus Electronic GmbH, Germany), a portable non-destructive diagnostic instrument widely employed for evaluating internal wood properties in standing trees.

ERT measurements were conducted at breast height (1.37 m above ground level). Depending on stem circumference, 24 stainless-steel electrodes were positioned uniformly around the stem at equal angular intervals (Divakara et al., 2020; Divakara and Chaithra, 2022). Small nails were inserted carefully through the bark into the conductive xylem tissue to establish electrical contact while minimizing mechanical injury to the tree. The TreeTronic instrument sequentially injected low-intensity electrical currents between electrode pairs while simultaneously measuring the resulting electrical potential differences among all remaining electrodes. The acquired resistance measurements were processed using PiCUS TreeTronic software, which reconstructed two-dimensional tomographic images representing the spatial distribution of electrical resistivity across the stem cross-section.

Each tomogram was automatically colour-coded according to resistivity values:

- **Blue to dark blue** – very low electrical resistance (high moisture content)
- **Green** – low to moderate resistance
- **Yellow** – intermediate resistance
- **Orange to red** – high electrical resistance
- **Dark red to brown** – very high resistance representing dry, compact heartwood

The reconstructed images provide qualitative and semi-quantitative information regarding internal wood condition without causing permanent damage to the tree (Figure 1).

2.5 Interpretation of Tomographic Images

Tomographic images were interpreted by integrating electrical resistivity patterns with principles of wood anatomy, moisture distribution, and tree physiology.

Interpretation focused on the following characteristics:

Heartwood development

Continuous high-resistance zones occupying the central stem region were interpreted as well-developed, compact heartwood possessing relatively low moisture content.

Sapwood distribution

Peripheral low-resistance zones surrounding the heartwood represented physiologically active sapwood involved in water transport.

Moisture anomalies

Localized low-resistance patches occurring within the heartwood zone were interpreted as areas of elevated internal moisture, potentially indicating physiological heterogeneity, localized water accumulation, or early stages of internal deterioration.

Structural continuity

The continuity of resistivity patterns across the stem cross-section was examined to identify discontinuities, cavities, or extensive internal defects.

Decay and hollowness

Continuous diffuse low-resistance regions lacking normal radial zonation were considered indicative of moisture-rich deteriorated wood. Sharply bounded central low-resistance regions would indicate advanced decay or hollowness. Conversely, diffuse low-resistance anomalies without distinct cavity formation were interpreted cautiously as moisture heterogeneity requiring further monitoring rather than definitive decay.

Interpretations were supported by external field observations and, where necessary, confirmatory increment core sampling described in the report.

2.6 Structural Health Classification

Based on the ERT observations, each tree was classified into one of three structural health categories.

Category I – Structurally sound trees possessing (i) Continuous heartwood, (ii) Distinct radial differentiation, (iii) No evidence of hollowness, (iv) Minimal moisture anomalies and (v) Good structural continuity these trees were considered suitable for Heritage Tree designation.

Category II – Moderately sound trees exhibiting (i) Partial heartwood development, (ii) Localized moisture-rich regions, (iii) Minor internal heterogeneity and (iv) No major structural discontinuity, these trees were considered suitable with periodic monitoring.

Category III – Conditionally suitable trees characterized by (i) Limited heartwood development, (ii) Extensive moisture-rich wood, (iii) Diffuse low-resistance zones, (iv) Potential early deterioration and (v)

No complete hollowness, these trees were considered conditionally suitable, requiring detailed inspection and continuous monitoring before final heritage designation.

2.7 Data Analysis

The ERT images were analysed qualitatively by comparing internal resistivity distribution among tree species and individual trees. Each tomogram was evaluated for (i) Radial resistivity pattern

(ii) Extent of heartwood development, (iii) Distribution of sapwood, (iv) Internal moisture heterogeneity, (v) Presence or absence of hollowness, (vi) Structural continuity and (vii) Internal anomalies

The frequency of different structural health categories was calculated and expressed as percentages. Comparative analyses were performed to identify common resistivity patterns among species and to evaluate the prevalence of structurally sound, moderately sound, and conditionally suitable trees.

Descriptive statistics were used to summarize structural health characteristics. Where quantitative resistivity values were available, minimum and maximum resistance ranges were documented to facilitate comparison among species and improve interpretation of heartwood and moisture distribution. These analyses formed the basis for evaluating the suitability of candidate trees for heritage designation and for developing objective criteria for incorporating Electrical Resistance Tomography into urban tree conservation programmes.

3. Results and Discussion

In the present assessment, selected heritage trees in Chennai were evaluated using VTA and ERT. A total of 52 trees representing different species were assessed for visible structural defects, stem girth and ERT resistivity characteristics. Based on the combined observations, each tree was assigned a heritage-tree suitability status as suitable, conditionally suitable, or not suitable for inclusion under the Heritage Tree category (Table 1).

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
1	*Hardwickia binata*	A few branch cuts are observed, which may act as potential entry points for moisture ingress into the heartwood zone	230	24–7601 Ω	70%	Conditionally suitable
2	*Madhuca longifolia*	A few branch cuts are observed, which may act as potential entry points for moisture ingress into the heartwood zone. Also few canker like structures are visible	336	170–480 Ω	90%	Conditionally suitable
3	*Syzygium cumini*	A few branch cuts are observed, which may act as potential entry points for moisture ingress into the heartwood zone	280	147–463 Ω	90%	Conditionally suitable
4	*Dolichandrone falcata*	A cavity-like damage is observed on one side of the tree trunk and several primary and secondary branches are cut or broken	144	158–388 Ω	100%	Suitable
6	*Tamarindus indica*	The bark is peeled off on one side of the tree, exposing a dry stem surface. Additionally, several primary and secondary branches are cut or broken	432	413–6266 Ω	80%	Conditionally suitable
7	*Adansonia digitata*	Few primary and secondary branches are cut/broken	180	103–134 Ω	100%	Suitable
8	*Swietenia mahagoni*	One of the main branch and few secondary branches are cut/broken	348	235–3252 Ω	90%	Conditionally suitable
9	*Swietenia mahagoni*	Few primary and secondary branches are cut/broken	360	215–596 Ω	90%	Conditionally suitable

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
10	*Morinda pubescens*	Few primary and secondary branches are cut/broken	230	451–2501 Ω	100%	Suitable
11	*Prosopis cineraria*	Few primary and secondary branches are cut/broken		952–1590 Ω	100%	Suitable
12	*Putranjiva roxburghii*	Some portion of the tree is hallow but not damaged. Few primary and secondary branches are cut/broken.	348	69–889 Ω	50%	Conditionally Suitable
13	*Guaiacum officinale*	One of the main branch and few secondary branches are cut.	324	233–2271 Ω	50%	Conditionally suitable
14	*Putranjiva roxburghii*	Few secondary branches are cut/broken.	243	86–268 Ω	70%	Conditionally suitable
15	*Terminalia arjuna*	A large cavity-like damage is observed on one side of the tree trunk, and a few primary and secondary branches are cut or broken.	312	20–757 Ω	80%	Conditionally suitable
16	*Prosopis cineraria*	One of the two main branches is cut/broken.	120	60–97 Ω	20% ,	Not-suitable for inclusion under the Heritage Tree category
17	*Butea monosperma*	Few secondary branches are cut/broken.	122	64–144 Ω	100%	suitable
19	*Prosopis cineraria*	One of the main branches has been cut, creating a potential entry point for water ingress.		13–1167 Ω	90%	Conditionally suitable
21	*Anogeissus acuminata*	Few primary and secondary branches are cut/broken. A hole	432	24–332 Ω	80%	Conditionally suitable

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
		is observed at the top of the bole.				
22	*Neolamarckia kadamba*	Few secondary branches are cut/broken.	180	91–177 Ω	100%	Suitable
23	*Bombax malabaricum*	Few secondary branches are cut/broken.	264	53–145 Ω	100%	Suitable
26	*Schleisera oleosa*	Few primary and secondary branches are cut/broken.	456	68–410 Ω	70%	Conditionally suitable
27	*Hura creptians*	Bulges are observed at multiple locations along the bole, and a few branches are cut/broken.	324	83–127 Ω	50%	Conditionally suitable
28	*Putranjiva roxburghii*	Few secondary branches are cut/broken.	324	56–1257 Ω	50%	Conditionally suitable
34	*Anogeissus acuminata*	The tree exhibits extensive cankerous growth along the entire bole, with approximately 50% of the main stem being hollow. Additionally, several primary and secondary branches have been cut/broken.	588	27–70,609 Ω	20%	Not-suitable for inclusion under the Heritage Tree category
35	*Azadirachta indica*	The tree is affected by canker-like growths along the main stem, along with the presence of a few cut branches.	552	153–1470 Ω	50%	Conditionally suitable
36	*Elaeodendron glaucum*	Some primary and secondary branches are damaged, which may allow water to enter the main stem. In addition, fungal fruiting bodies are observed at the base of the main stem,	652	94–497 Ω	50%	Conditionally suitable

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
		indicating possible fungal colonisation.				
40	*Diospyros malabarica*	Some secondary branches are damaged, which may allow water to enter the main stem. In addition, fungal fruiting bodies are observed at the base of the main stem, indicating possible fungal colonisation.	336	190–1666 Ω	100%	Suitable
41	*Adansonia digitata*	Several primary and secondary branches have been cut, accompanied by bark damage, which may facilitate water ingress into the stem.	384	75 – 189 Ω	100%	Suitable
42	*Adansonia digitata*	Some secondary branches have been cut, which may serve as entry points for water ingress into the stem.	1104	176–432 Ω	100%	Suitable
43	*Terminalia bellerica*	The main apical portion of the tree and several primary branches have been cut, potentially serving as entry points for water ingress into the stem.	228	24–31 Ω	20%	Not suitable for inclusion under the Heritage Tree category
44	*Swietenia mahagoni*	A hole at the branch forking point and visible cuts on some of the main branches may serve as entry points for water ingress into the main stem.	276	760–1772 Ω	100%	Suitable
45	*Terminalia arjuna*	Canker-like lesions are visible along the bole, and several branch cuts are present, which may act as	480	37–315 Ω	50%	Conditionally suitable

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
		potential entry points for water ingress into the stem				
47	*Adansonia digitata*	Some branches have been cut, creating potential entry points for water ingress into the stem.	1067	73–2160 Ω	70%	Conditionally suitable
48	*Sterculia foetida*	Some branches have been cut, creating potential entry points for water ingress into the stem.	354	60–286 Ω	50%	Conditionally suitable
51	*Madhuca longifolia*	The tree exhibits extensive canker-like growths distributed along the main stem as well as on both primary and secondary branches. These abnormal swellings and lesions suggest chronic tissue damage and possible pathogenic infection affecting multiple parts of the tree.	225	140–212 Ω	50%	Conditionally suitable
54	*Azadirachta indica*	No major structural damage is evident in the tree.	316	228–7521 Ω	100%	Suitable
55	*Strychnos nux-vomica*	Some main branches and several secondary branches have been cut. The cut ends are dried, indicating older pruning wounds. Several knot-like swellings or growths are observed along the main stem.	300	666–4116 Ω	90%	Conditionally suitable
57	*Terminalia arjuna*	A few branch cuts are observed, which may act as potential entry points for moisture ingress into the heartwood zone.	305	30–49 Ω	20%	Not suitable for inclusion under the Heritage Tree category

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
58	*Terminalia arjuna*	The tree exhibits evidence of recent and past pruning interventions. Two primary branches have been cut, and one fallen branch shows a visible cavity (hole) on one side. These exposed pruning wounds may serve as potential entry points for moisture ingress and pathogenic organisms, thereby increasing the risk of localized internal decay development within the heartwood zone	394	25–443 Ω	50%	Conditionally suitable
59	*Barringtonia acutangula*	No damage branch	300	608–2719 Ω	100%	Suitable
60	*Mimusops elengi*	Some of the main and secondary branches have cut end, which may act as potential entry points for moisture ingress into the heartwood zone.	384	216–541 Ω	60%	Suitable
61	*Swietenia mahagoni*	A major branch cut is observed on the tree. The exposed pruning wound represents a potential pathway for moisture ingress into the stem tissues. If not properly compartmentalized, such open cut surfaces can facilitate the entry of water, fungal spores, and wood-decaying organisms, increasing the risk of internal degradation extending toward the heartwood zone.	204	280–916 Ω	100%	Suitable

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
63	*Syzygium cumini*	Holes are observed at the cut ends of the tree branches. These cavities likely indicate localized decay development at the pruning sites. Such openings may result from fungal colonization, wood-boring insects, or progressive tissue breakdown following improper or large branch cuts.	325	265–644 Ω	70%	Suitable
64	*Barringtonia acutangula*	Small damage is noticed at the place of forking	189	51–83 Ω	70%	Conditionally suitable
67	*Azadirachta indica*	A few branch cuts are observed, which may act as potential entry points for moisture ingress into the heartwood zone.	360	145–493 Ω	50%	Conditionally suitable
68	*Anogeissus acuminata*	Visible damage is observed on the tree trunk. In addition, several secondary branches have been cut. Pruning cuts are large or improperly executed, they may delay natural compartmentalization and increase susceptibility to localized decay development.	293	187–607 Ω	50%	Conditionally suitable

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
69	*Anogeissus acuminata*	Main and secondary branches have been cut. Pruning cuts are large or improperly executed, they may delay natural compartmentalization and increase susceptibility to localized decay development.	416	120–4147 Ω	70%	Conditionally suitable
70	*Swietenia mahagoni*	The tree exhibits significant structural and pathological concerns. The presence of dry and dead main branches. Fruiting bodies observed at the base of the tree are of particular concern. Additionally, several branches have been cut due to adjacent building clearance. The exposed cut surfaces remain open, creating pathways for moisture ingress and fungal infection. Such wounds can accelerate decay progression from the outer tissues toward the heartwood.	295	371–1329 Ω	100%	Suitable
71	*Azadirachta indica*	Holes are observed at the cut ends of the tree branches. These cavities likely indicate localized decay development at the pruning sites. Such openings may result from fungal colonization, wood-boring insects, or progressive tissue breakdown following improper or large branch cuts. Entire bark discoloration is	383	451–1774 Ω	80%	Suitable

Table 1. Details of Heritage tree selected in Chennai

Tree no.	Tree species	Visual tree assessment (VTA)	Girth (cm)	ERT Resistivity	Heritage tree suitability	Remarks
		seen all along the stem.				
72	*Lannea coromandelica*	The tree appears healthy, with no visible signs of external damage or physiological stress. The trunk surface is intact, and no cracks, cavities, fungal fruiting bodies, or mechanical injuries are observed. The canopy structure is well-formed, with no evident dieback, dead branches, or abnormal leaf discoloration.	304	198–1931 Ω	100%	Suitable
73	*Tamarindus indica*	Main and secondary branches have been cut. Pruning cuts are large or improperly executed, they may delay natural compartmentalization and increase susceptibility to localized decay development.	376	70–263 Ω	100%	Suitable
77	*Swietenia mahagoni*	No major structural damage is evident in the tree.	326	262–925 Ω	90%	Suitable

3.1 Electrical Resistance Tomography Revealed Distinct Internal Wood Structure

The Electrical Resistance Tomography (ERT) assessment successfully characterized the internal structural condition of all 52 candidate heritage trees representing more than 20 species by mapping spatial variations in electrical resistivity across the stem cross-sections. Considerable variation in resistivity was observed both within individual stems and among species, with recorded values ranging from approximately 13 Ω to more than 70,000 Ω. This wide variation reflects differences in wood moisture content, heartwood development, wood density, extractive concentration, anatomical characteristics, and internal structural condition.

The tomograms generally showed a distinct radial pattern, with relatively low resistivity towards the peripheral sapwood, intermediate values in the transition zone, and higher resistivity towards the inner heartwood region. This pattern is consistent with the physiological and anatomical differences between sapwood and mature heartwood. Sapwood generally contains higher amounts of moisture and mobile ions and therefore conducts electrical current more readily, whereas mature heartwood is comparatively less conductive because of its lower moisture content and greater accumulation of extractives and secondary metabolites. Similar applications of ERT for distinguishing sapwood, heartwood, and internal wood conditions have been reported in living trees (Guyot et al., 2013; Bär et al., 2019).

Considerable interspecific variation was observed in the extent, continuity, and distribution of heartwood. Such variation may be associated with differences in species, tree age, growth rate, wood anatomy, heartwood formation, extractive content, and environmental conditions. Most of the assessed trees exhibited extensive and relatively continuous high-resistivity cores, indicating well-developed mature wood and comparatively stable internal conditions. Species such as *Hardwickia binata*, *Madhuca longifolia*, *Syzygium cumini*, *Dolichandrone falcata*, *Tamarindus indica*, *Morinda pubescens*, *Prosopis cineraria*, *Terminalia arjuna*, and several individuals of *Swietenia mahagoni* showed substantial heartwood development.

The observed resistivity patterns should, however, be interpreted with caution because electrical resistivity is influenced by several interacting factors. Ganthaler et al. (2019) reported that low resistivity may be associated with increased moisture content, higher electrolyte concentration, and/or lower wood density. Therefore, a low-resistivity zone cannot automatically be interpreted as decay. Its significance depends on its size, location, continuity, and distribution within the stem, as well as the biological characteristics of the species and the prevailing environmental conditions.

In the present study, some trees exhibited localized, irregular, and discontinuous low-resistivity regions within the inner stem. These areas were interpreted as possible variations in moisture content, electrolyte concentration, or incomplete heartwood differentiation rather than definitive evidence of advanced internal decay. Importantly, none of the assessed trees showed a large, continuous, sharply defined low-resistivity region extending through the central stem that would strongly suggest extensive hollowness or severe internal deterioration.

The absence of extensive continuous low-resistivity zones, together with the presence of substantial high-resistivity cores in most trees, indicates that the majority of the assessed heritage trees retained considerable internal structural continuity. This finding is particularly important because several trees exhibited external defects that could not, by themselves, provide conclusive evidence of internal structural impairment.

Overall, the results demonstrate that ERT is an effective non-destructive technique for visualizing internal resistivity patterns and assessing the structural condition of heritage trees. However, resistivity values should not be interpreted using a single universal threshold across different species. As emphasized by Bär et al. (2019), species-specific differences and variations in moisture, wood anatomy, density, and

electrolyte content must be considered during interpretation. The present findings therefore support the use of ERT in combination with Visual Tree Assessment (VTA) and other relevant tree-health observations to distinguish normal physiological variation from potentially significant internal structural defects.

3.2 Internal Structural Integrity of Heritage Trees

The majority of the assessed heritage trees exhibited good to excellent internal structural integrity, as indicated by extensive and continuous heartwood occupying a substantial portion of the stem cross-section. Species such as *Hardwickia binata*, *Madhuca longifolia*, *Syzygium cumini*, *Dolichandrone falcata*, *Tamarindus indica*, *Morinda pubescens*, *Prosopis cineraria*, *Terminalia arjuna*, and several individuals of *Swietenia mahagoni* showed well-developed heartwood with a clear distinction from the surrounding sapwood. The corresponding ERT tomograms generally showed continuous high-resistivity regions, with no clear evidence of large internal cavities, extensive decay, or major structural discontinuities. Similar species-related and within-tree variation in ERT patterns has been reported by Bär et al. (2019) and Ganthaler et al. (2019).

The relatively high electrical resistance observed in the heartwood may be associated with its lower moisture content and the accumulation of extractives and other secondary metabolites during heartwood formation. These characteristics contribute to differences in the electrical properties of mature wood and can be effectively visualized through ERT (Ganthaler et al., 2019).

Several trees showed asymmetric or eccentric heartwood distribution; however, this feature should not be considered, by itself, as evidence of structural deterioration. Irregular heartwood formation may occur in response to eccentric stem growth, stem inclination, prevailing wind, uneven mechanical loading, and reaction-wood formation. Studies have demonstrated a relationship between eccentric stem growth, wind exposure, and irregular heartwood formation (Stokes et al., 2000; Berthier et al., 2001).

Although some trees exhibited variations in the symmetry and distribution of heartwood, the high-resistivity core generally remained continuous. Therefore, eccentric heartwood formation alone is unlikely to indicate serious structural weakness in the absence of associated decay, cavities, or extensive loss of sound wood. ERT interpretation should consequently consider the biological characteristics and growth history of individual trees rather than relying solely on the geometric symmetry of the heartwood (Bär et al., 2019; Ganthaler et al., 2019).

The majority of the assessed trees therefore demonstrated satisfactory to excellent internal structural condition, with substantial continuous heartwood and no evidence of extensive cavities, severe decay, or major internal discontinuities. This was particularly evident in several large and mature trees where considerable internal wood continuity was maintained despite external signs of previous injury or management.

The results further indicate that irregular heartwood boundaries should not automatically be considered an indication of reduced structural stability. Mature trees commonly develop non-uniform radial growth

because of environmental and mechanical influences, including wind, stem inclination, crown asymmetry, competition, and previous injury. Such adaptive growth may result in eccentric wood formation while maintaining continuity of the stem (Stokes et al., 2000; Berthier et al., 2001).

Thus, the structural significance of eccentric or irregular heartwood should be evaluated in relation to the continuity and extent of sound wood, presence of decay or cavities, and overall tree architecture, rather than on symmetry alone. This interpretation is especially important for heritage trees, which frequently exhibit irregular growth patterns resulting from long-term environmental exposure. The findings suggest that an irregular heartwood boundary, in the absence of significant internal deterioration, should not by itself result in downgrading the structural or heritage status of a tree.

3.3 Moisture-Rich Internal Zones and their Structural Significance

Several heritage trees exhibited localized areas of comparatively low electrical resistance within the heartwood. These regions were generally diffuse, irregular, and limited in extent rather than sharply defined or cavity-like. Importantly, increment-core sampling carried out on selected representative trees confirmed that some of these low-resistance regions were associated with moisture-rich wood rather than empty cavities or advanced decay. This observation emphasizes the importance of validating anomalous ERT patterns using direct or complementary diagnostic methods where necessary.

Electrical resistivity in wood is influenced by several factors, including moisture content, electrolyte concentration, temperature, wood density, and anatomical characteristics. Therefore, a reduction in electrical resistance should not be interpreted automatically as evidence of decay or structural deterioration. Ganthaler et al. (2019) reported that low resistivity may be associated with increased moisture content, higher electrolyte concentration, or lower wood density, and that the relative influence of these factors may vary among species and within different portions of the stem.

The moisture-rich regions detected in the present study may have resulted from several physiological or structural processes, including incomplete heartwood formation, localized water accumulation, internal water redistribution, wound responses, compartmentalization, and age-related physiological changes. These processes may produce localized low-resistivity areas while the surrounding wood remains continuous and structurally competent. Thus, the findings emphasize the importance of distinguishing low-resistivity wood from genuinely decayed wood during interpretation of ERT tomograms.

The observations are consistent with Nicolotti et al. (2003), who reported that low-resistivity regions can be associated with decayed or moisture-rich wood and emphasized the need for careful interpretation of electrical tomographic images. Similarly, Ganthaler et al. (2019) demonstrated that electrical resistivity is affected by moisture, electrolyte concentration, wood density, and other anatomical characteristics. These findings indicate that resistivity values should preferably be interpreted in combination with visual symptoms, tree biology, and additional diagnostic information rather than using a single resistivity threshold to identify decay.

A limited number of trees, particularly *Putranjiva roxburghii* and *Guaiacum officinale*, exhibited comparatively extensive low- to moderate-resistivity regions together with limited heartwood differentiation. Although these trees retained continuous internal wood and did not show evidence of complete hollowness, the relatively smaller proportion of well-developed heartwood may indicate comparatively lower structural resilience than trees possessing extensive and continuous mature heartwood. Persistent moisture-rich conditions could also increase the possibility of future deterioration if accompanied by biological degradation, repeated injury, or other predisposing factors. Accordingly, these individuals were considered conditionally suitable for heritage-tree designation, with periodic structural assessment and monitoring recommended.

The present findings demonstrate that localized low-resistivity regions in ERT tomograms should be interpreted cautiously and within the physiological and structural context of individual trees. Where anomalous patterns are detected, confirmation through increment-core sampling, resistance drilling, sonic or ultrasonic tomography, or repeated ERT measurements can improve diagnostic confidence. The combined use of complementary diagnostic techniques has been recommended in tree-decay assessment because no single non-destructive method can reliably distinguish all forms of internal moisture variation and decay under different tree and environmental conditions (Nicolotti et al., 2003; Bär et al., 2019; Ganthaler et al., 2019).

Overall, the results indicate that the presence of localized low-resistance zones does not necessarily represent structural failure. Instead, their shape, extent, continuity, location, and association with other evidence should be considered before classifying them as internal defects. This approach provides a more reliable basis for assessing the structural condition and conservation suitability of heritage trees.

3.4 Heritage Tree Suitability Assessment/ Classification

The final assessment of heritage-tree suitability was carried out by integrating the findings of Visual Tree Assessment (VTA) and Electrical Resistance Tomography (ERT). This combined approach enabled the evaluation of both visible defects and internal structural conditions. Based on the overall assessment, the trees were classified into three categories: (i) Suitable for Heritage Tree Designation, (ii) Conditionally Suitable for Heritage Tree Designation, and (iii) Not Suitable for Immediate Heritage Tree Designation.

This classification provided a more comprehensive assessment than relying only on external appearance, as VTA and ERT provide complementary information. VTA helps identify visible defects, tree architecture, vitality, and external symptoms that may indicate internal problems, while ERT provides information on the internal condition and structural integrity of the stem. The VTA approach developed by Mattheck and Breloer uses external growth patterns and morphological characteristics as indicators of possible internal defects, which can then be examined using more detailed diagnostic techniques.

3.4.1 Suitable for Heritage Tree Designation

Trees assigned to this category exhibited good internal structural continuity, well-developed heartwood, and no significant evidence of decay, extensive hollowness, or major internal discontinuities. Although some individuals had external defects such as old pruning wounds, superficial bark injuries, or minor mechanical damage, these defects were not associated with appreciable internal deterioration in the ERT images.

Representative species included *Dolichandrone falcata*, *Adansonia digitata*, *Morinda pubescens*, *Bombax malabaricum*, *Diospyros malabarica*, *Barringtonia acutangula*, *Swietenia mahagoni*, *Lannea coromandelica*, and *Tamarindus indica*. These trees showed high structural integrity and satisfactory internal wood condition, and were therefore considered suitable for heritage-tree designation. Continued routine monitoring through periodic visual inspection is recommended to ensure that emerging defects are identified at an early stage.

3.4.2 Conditionally Suitable for Heritage Tree Designation

Trees in this category exhibited moderate structural limitations, with estimated suitability ranging from approximately 50 to 90%. The observed conditions included uneven or asymmetric heartwood development, localized areas of increased moisture, early-stage internal deterioration, pruning injuries, bark damage, fungal activity, and small cavities.

The category included *Hardwickia binata*, *Madhuca longifolia*, *Syzygium cumini*, *Terminalia arjuna*, *Putranjiva roxburghii*, *Guaiacum officinale*, *Schleichera oleosa*, *Sterculia foetida*, *Strychnos nux-vomica*, and *Azadirachta indica*. Despite the presence of these limitations, the trees generally retained adequate internal continuity and sufficient structural stability.

Considering their potential ecological, historical, and cultural importance, these trees may be considered for heritage designation subject to appropriate management measures. Periodic VTA should be undertaken, while repeat ERT assessment or other diagnostic investigations may be considered where progressive deterioration is suspected. Necessary arboricultural interventions should be implemented to control existing defects and reduce the likelihood of further structural decline.

3.4.3 Not Suitable for Immediate Heritage Tree Designation

Only a few trees were classified as not suitable for immediate heritage-tree designation, primarily because of severe internal deterioration and associated structural concerns. *Prosopis cineraria*, *Anogeissus acuminata*, *Terminalia bellerica*, and severely affected individuals of *Terminalia arjuna* recorded an estimated suitability of approximately 20%.

These trees exhibited one or more serious structural defects, including extensive hollowness, large internal cavities, advanced decay, severe canker development, and extensive moisture-dominated internal zones. The ERT results indicated substantial deterioration of structurally competent wood, suggesting an increased risk of stem or branch failure.

Although these trees may have considerable ecological, historical, or cultural significance, their present structural condition does not support immediate heritage designation. A detailed structural risk assessment should therefore be undertaken before any final decision regarding designation. Where conservation and retention are considered important, appropriate remedial measures and intensive monitoring using VTA, ERT, or other suitable diagnostic techniques should be implemented.

The three-tier classification demonstrates the added value of integrating external visual assessment with non-destructive internal diagnostics. VTA effectively identifies visible defects and provides an initial indication of tree condition, whereas ERT reveals internal characteristics such as heartwood development, moisture distribution, decay, hollowness, and structural discontinuities that may not be apparent externally.

The findings indicate that visible defects alone should not be used as the sole criterion for determining heritage-tree suitability. Trees with substantial external injuries may retain satisfactory internal structural integrity, while apparently sound trees may contain concealed deterioration. The integrated VTA–ERT approach therefore provides a more objective and evidence-based basis for heritage-tree designation, prioritization of monitoring, and formulation of appropriate arboricultural management and conservation measures.

3.5 Implications for Urban Tree Conservation and Risk Assessment

The findings clearly demonstrate that Electrical Resistance Tomography (ERT) is an effective decision-support tool for the scientific assessment and management of heritage trees. Visual Tree Assessment (VTA) is useful for identifying external defects, growth abnormalities, wounds, cavities, fungal symptoms, and other visible indicators of structural weakness. However, visual assessment alone may not provide sufficient information about the extent and location of internal deterioration. Therefore, ERT can complement VTA by providing information on internal wood conditions, including sound wood, moisture-rich regions, decay, and hollow areas (Mattheck and Breloer, 1994; Yue et al., 2019).

For heritage trees, where destructive sampling is generally undesirable, ERT provides a useful non-destructive approach for evaluating internal structural condition while minimizing damage to valuable trees. The technique can provide spatial information on internal wood characteristics and assist arborists and tree managers in identifying trees requiring intervention, distinguishing structurally sound trees from potentially compromised individuals, and developing appropriate monitoring programmes (Yue et al., 2019).

The absence of extensive hollowness or advanced internal deterioration in most of the examined trees also indicates that mature trees can retain considerable structural integrity despite their advanced age and visible external defects. Consequently, tree age or external appearance alone should not be used as the primary basis for decisions regarding tree removal. VTA itself emphasizes the interpretation of

external symptoms and, where necessary, confirmation of suspected defects through additional diagnostic methods (Mattheck and Breloer, 1994).

The integration of ERT with VTA therefore provides a more comprehensive basis for heritage-tree management by combining external observations with information on internal structural conditions. Such an integrated approach can help reduce unnecessary removal of valuable mature trees while enabling timely management of trees showing significant structural deterioration. This approach is particularly relevant for heritage trees because their ecological, cultural, historical, and social values need to be considered alongside structural safety.

Based on the present findings, a tiered management framework can be proposed for heritage-tree conservation.

Suitable trees

Trees showing continuous sound wood, well-developed heartwood, and no evidence of major internal defects may be prioritized for heritage-tree designation. These trees should undergo routine VTA at appropriate intervals, while ERT can be repeated when new external symptoms or changes in tree condition indicate the possibility of internal deterioration (Mattheck and Breloer, 1994; Yue et al., 2019).

Conditionally suitable trees

Trees showing localized moisture anomalies, asymmetric heartwood, minor cavities, fungal activity, pruning wounds, or early signs of deterioration may be retained when their heritage value justifies continued conservation. Appropriate arboricultural measures, including corrective pruning where necessary, wound protection, management of fungal problems, reduction of avoidable mechanical stress, and periodic reassessment, should be considered. Repeat ERT assessment may be useful where progressive internal deterioration is suspected.

Trees not suitable for designation

Trees exhibiting extensive cavities, advanced decay, major loss of sound wood, severe cankers, or other substantial structural defects should undergo detailed tree-risk assessment before a final management decision is made. Even in such cases, the cultural or historical significance of the tree should be considered together with the likelihood of failure, target exposure, and consequences of failure. Tree-risk assessment generally requires consideration of tree defects, likelihood of failure, likelihood of impacting a target, and potential consequences (Mattheck and Breloer, 1994).

This tiered approach allows heritage conservation and public safety to be considered together. Importantly, ERT should not replace professional arboricultural judgement; rather, it should provide additional objective information to reduce uncertainty in the assessment of internal tree condition. Previous studies have demonstrated that ERT can provide useful information for detecting and

characterizing internal decay in standing trees, particularly during earlier stages of deterioration (Yue et al., 2019).

The findings therefore highlight the practical value of combining ERT and VTA for the conservation and management of heritage trees. VTA remains essential for evaluating crown architecture, visible defects, wounds, cavities, fungal fruiting bodies, bark condition, and other external symptoms, while ERT provides complementary information on internal structural characteristics. Visual inspection may indicate the presence of internal defects, but additional diagnostic techniques are often required to determine their extent and severity (Mattheck and Breloer, 1994).

The absence of extensive hollowness or advanced decay in most of the assessed trees is particularly important from a conservation perspective. Advanced age alone should not be considered sufficient justification for tree removal. Mature trees may retain substantial structural continuity despite old wounds, external defects, and irregular growth patterns. Management decisions should instead consider the available evidence on structural condition, probability of failure, target exposure, and consequences of potential failure (Mattheck and Breloer, 1994; Yue et al., 2019).

The results further support a shift from a predominantly reactive approach towards preventive and evidence-based heritage-tree management. Trees classified as suitable can be maintained through routine visual inspection and preventive care, whereas conditionally suitable trees should receive more intensive monitoring and appropriate arboricultural intervention. Trees showing serious internal deterioration require detailed risk assessment and, where technically feasible, stabilization or other risk-reduction measures. Periodic reassessment using VTA and, where indicated, ERT can help determine whether the internal condition remains stable or is progressively deteriorating.

3.6 Integration of Visual Tree Assessment (VTA) and Electrical Resistance Tomography (ERT)

A total of 52 candidate heritage trees, representing more than 20 species, were evaluated using an integrated approach involving Visual Tree Assessment (VTA) and Electrical Resistance Tomography (ERT). The assessed trees showed considerable variation in stem size, pruning history, bark condition, crown architecture, and visible symptoms of injury or deterioration. Stem girth ranged from approximately 120 to 1104 cm, representing a wide spectrum of mature trees as well as exceptionally large and old individuals.

Visual Tree Assessment identified a range of external defects, including pruning wounds, mechanical injuries, bark damage, cavities, hollows, canker-like lesions, bark peeling, and fungal fruiting bodies. Among these defects, pruning-related injuries were particularly common. Such injuries were frequently observed in roadside trees and trees growing in public parks, where repeated branch removal is often carried out to maintain clearance from roads, buildings, electrical lines, and other infrastructure. Poorly managed pruning wounds can provide entry points for moisture and microorganisms and may contribute to the development and progression of internal decay (Mattheck and Breloer, 1994; Shigo, 1986).

Canker-like symptoms were recorded in *Madhuca longifolia*, *Terminalia arjuna*, *Azadirachta indica*, and *Anogeissus acuminata*. Fungal fruiting bodies were observed on *Elaeodendron glaucum*, *Diospyros malabarica*, and *Swietenia mahagoni*, indicating localized fungal activity. Prominent cavities or hollows were recorded in *Terminalia arjuna*, *Prosopis cineraria*, and *Anogeissus acuminata*. Bark peeling and other stem injuries were also observed in several individuals. Such defects may increase the exposure of underlying tissues to moisture and decay-causing organisms; however, the presence of an external defect does not necessarily indicate extensive internal deterioration.

This distinction was clearly demonstrated by the ERT observations. Several trees with prominent pruning wounds and other external defects retained continuous and relatively sound internal wood, with no clear evidence of advanced decay or extensive hollowness. This may be related to the ability of trees to compartmentalize wounds and restrict the progression of decay into surrounding tissues. The concept of compartmentalization of decay in trees indicates that wounded trees can develop chemical and anatomical barriers that restrict the spread of microorganisms and preserve substantial volumes of functional and structurally competent wood (Shigo, 1986).

Conversely, some trees with relatively minor external symptoms exhibited localized internal abnormalities that could not be readily identified through visual inspection alone. This observation highlights an important limitation of relying exclusively on external assessment for evaluating the structural condition of mature and heritage trees. Similar observations have been reported in studies comparing electrical resistance tomography with other non-destructive techniques, where tomographic methods provided additional information regarding internal decay and structural discontinuities that were not always apparent from external symptoms (Yue et al., 2019).

The results therefore demonstrate that VTA alone cannot reliably predict the complete internal structural condition of heritage trees. VTA remains an essential first-stage assessment technique because it provides valuable information on tree architecture, crown condition, wounds, cavities, fungal symptoms, bark abnormalities, and other visible indicators of potential structural problems (Mattheck and Breloer, 1994). However, the absence of obvious external symptoms cannot necessarily be interpreted as evidence that the internal stem is completely sound.

ERT provides an important complementary diagnostic capability by detecting spatial variations in electrical resistivity within the stem. Differences in electrical resistance are influenced by factors such as wood moisture, ionic concentration, wood structure, and decay-related changes, allowing areas with contrasting internal conditions to be visualized (Bieker et al., 2010; Yue et al., 2019). Consequently, ERT can assist in determining whether an externally visible defect is associated with significant internal deterioration and can also reveal concealed abnormalities that are not apparent from the stem surface.

The contrasting observations obtained from VTA and ERT further demonstrate that the two techniques should not be regarded as competing diagnostic approaches. Instead, they provide complementary information at different levels of tree assessment. VTA provides the initial assessment of external biological and structural characteristics, whereas ERT provides additional information regarding the

internal distribution of resistivity and the possible presence and extent of internal defects. The combination of these techniques therefore provides a more comprehensive understanding of overall tree condition.

The integrated VTA–ERT approach is particularly valuable for heritage trees because these trees often possess considerable ecological, cultural, historical, and social significance, making unnecessary destructive investigation or premature removal undesirable. By combining visible evidence with objective information on internal stem condition, the approach can reduce uncertainty in tree-risk assessment and support more scientifically defensible decisions concerning heritage designation, conservation, monitoring, arboricultural intervention, and long-term tree management.

Overall, the findings demonstrate that the assessment of heritage trees should not rely solely on tree age, external appearance, or the presence of individual defects. Instead, management decisions should be based on an integrated evaluation of external symptoms, internal structural condition, likelihood of failure, target exposure, and the consequences of potential failure. The combined application of VTA and ERT therefore represents a practical and scientifically supported framework for improving the assessment and conservation of valuable mature and heritage trees.

3.7 Electrical Resistance Tomography (ERT) Assessment

ERT successfully characterized the internal condition of all assessed trees by mapping spatial variations in electrical resistivity across the stem. The measured resistivity values varied widely, from approximately 13 Ω to more than 70,000 Ω, indicating considerable differences in moisture status, heartwood development, wood properties, and internal deterioration among the species evaluated. Such variation is expected because electrical resistivity in wood is influenced by moisture content, ionic concentration, anatomical characteristics, wood density, and the distribution of conductive and non-conductive tissues (Bieker et al., 2010; Yue et al., 2019).

Trees showing continuous areas of relatively high resistivity generally exhibited well-developed and structurally continuous heartwood, with no clear evidence of major internal deterioration. In contrast, predominantly low-resistivity regions were generally associated with moisture-rich tissues or deteriorated wood and, in some cases, corresponded with internal cavities or advanced degradation. However, interpretation of resistivity values should consider the overall tomographic pattern rather than relying on a single numerical value because resistivity can vary substantially within and among individual trees.

The exceptionally broad range of resistivity values observed in the present study also indicates substantial species-specific variation in electrical properties. Differences in wood anatomy, density, extractive content, moisture distribution, heartwood formation, and physiological condition can influence the resistivity response of standing trees. Consequently, a single universal resistivity threshold cannot be reliably applied to all heritage-tree species. Instead, the spatial distribution and relative contrast between different regions of the stem should be considered during interpretation.

Several species, including *Adansonia digitata, Barringtonia acutangula, Swietenia mahagoni, Tamarindus indica, Diospyros malabarica*, and *Lannea coromandelica*, exhibited relatively homogeneous resistivity patterns, indicating comparatively continuous internal wood structure despite the presence of moderate external pruning injuries. These observations further demonstrate that visible external defects do not necessarily correspond to extensive internal deterioration. The capacity of trees to compartmentalize wounds and restrict the progression of decay may contribute to the retention of substantial volumes of structurally sound wood even in trees with conspicuous external injuries (Shigo, 1986).

In contrast, trees exhibiting prominent cavities, fungal fruiting bodies, severe canker development, or pronounced stem hollowness showed more disrupted resistivity distributions. Such irregular patterns were consistent with localized moisture accumulation, altered wood condition, decay, or loss of continuous wood structure. These observations demonstrate the value of ERT in identifying internal abnormalities that may not be fully evident from external visual assessment alone.

The wide resistivity range recorded in the present investigation, from approximately 13 Ω to > 70,000 Ω, further emphasizes that ERT interpretation should be based on relative resistivity contrasts and tomographic patterns rather than rigid universal thresholds. Differences in wood anatomy, moisture content, density, extractive concentration, heartwood characteristics, and physiological status can all influence electrical measurements. Therefore, the same resistivity value may not necessarily represent the same wood condition across different tree species.

This observation is consistent with previous research demonstrating species-related variation in ERT responses. Bär et al. (2019) reported differences in electrical resistance patterns among *Betula pendula*, *Fagus sylvatica*, *Picea abies*, and *Pinus sylvestris*, and showed that differences in xylem properties can influence the resulting tomographic patterns. Their findings support the need to consider species-specific wood characteristics when interpreting electrical resistance measurements.

Environmental and methodological factors may also influence ERT measurements. Ganthaler et al. (2019) demonstrated that factors such as temperature, tree water status, and electrode installation conditions can affect electrical measurements and consequently influence tomographic interpretation. Seasonal changes in stem moisture are particularly important because increased moisture can reduce electrical resistance and potentially reduce the contrast between sound and deteriorated tissues. Therefore, measurements undertaken under substantially different environmental or seasonal conditions should be interpreted with appropriate caution.

The present findings consequently support the development of species-specific reference tomograms and resistivity databases for important heritage-tree species. Establishing reference ranges from healthy trees of different ages, stem sizes, and moisture conditions could improve the discrimination of normal heartwood, sapwood, moisture-rich tissues, decay, and cavities. Such databases would also facilitate more quantitative and reproducible interpretation of ERT results and strengthen its application as a decision-support tool in heritage-tree conservation.

Overall, the ERT results demonstrate that the technique provides valuable spatial information on internal stem condition and can complement conventional VTA. However, reliable interpretation requires consideration of species-specific characteristics, environmental conditions, tree water status, and measurement configuration. The development of standardized reference datasets, together with repeated measurements where necessary, would further enhance the reliability and practical application of ERT for long-term monitoring and management of heritage trees.

3.8 Relationship Between External Defects and Internal Structural Condition

One of the most important findings of the present investigation was that external appearance alone was not a reliable indicator of internal structural integrity. Several trees exhibiting extensive pruning wounds, bark damage, superficial cavities, or other visible defects nevertheless retained continuous and apparently sound internal wood, with little evidence of advanced decay. Conversely, some trees with relatively minor external symptoms exhibited substantial internal deterioration that was detected only through ERT. This observation highlights an important limitation of relying exclusively on visual inspection when evaluating mature and heritage trees. Visual Tree Assessment is primarily intended to identify external symptoms that may indicate underlying defects, while deeper diagnostic assessment may be required when internal deterioration is suspected (Mattheck and Breloer, 1994).

For example, several *Adansonia digitata* trees had undergone repeated branch removal but nevertheless retained apparently intact internal wood structure. Similarly, *Swietenia mahagoni* individuals with prominent pruning wounds frequently exhibited continuous and relatively sound heartwood. In contrast, certain *Terminalia arjuna* and *Prosopis cineraria* trees with comparatively modest external symptoms showed extensive internal weakening when assessed using ERT. These observations demonstrate that the severity of an external defect does not necessarily correspond directly to the extent of internal deterioration.

The observed discrepancy between external symptoms and internal condition is biologically plausible because trees possess mechanisms of wound response and compartmentalization that can restrict the spread of decay from injured tissues into surrounding wood. Consequently, an old wound or conspicuous pruning injury may remain localized without resulting in extensive loss of structurally competent wood. Conversely, internal decay can develop beneath apparently intact bark and may remain visually undetectable until deterioration becomes relatively advanced.

The findings therefore reinforce that VTA and ERT should be considered complementary rather than alternative diagnostic approaches. VTA provides important information on crown architecture, visible defects, wounds, cavities, bark condition, fungal symptoms, and other external indicators of potential structural problems. ERT, in contrast, provides spatial information on the internal distribution of electrical resistivity and can assist in identifying internal abnormalities that cannot be reliably inferred from surface observations alone. Previous research has demonstrated that electrical resistance tomography

can be useful for detecting and characterizing internal decay in standing trees, particularly during relatively early stages of deterioration (Yue et al., 2019).

The practical implication is that a purely visual assessment may result in two contrasting types of management error. Trees with conspicuous but localized external defects may be unnecessarily downgraded or considered unsuitable for conservation, whereas trees with limited visible symptoms but substantial concealed deterioration may be incorrectly regarded as structurally sound. Integrating VTA with ERT can substantially reduce this uncertainty by combining information on external tree condition with objective evidence of internal stem structure.

The present study demonstrates the practical value of Electrical Resistance Tomography as a decision-support tool for evidence-based heritage-tree management. ERT provides a minimally invasive method for investigating internal stem condition while avoiding extensive drilling or destructive sampling. This characteristic is particularly important when assessing historically, culturally, or ecologically significant trees for which unnecessary injury should be minimized. Electrical resistance tomography has been recognized as a promising minimally invasive technique for investigating the internal properties of living tree stems (Bär et al., 2019).

Based on the integrated VTA–ERT assessment, three broad management strategies can be recommended.

Suitable trees

Trees exhibiting continuous sound wood, well-developed heartwood, and no evidence of major internal defects may be considered suitable for heritage-tree designation. Such trees should be retained and subjected to routine health and structural inspections. ERT can be repeated when new defects, changes in tree condition, fungal activity, cavities, or other symptoms suggest possible internal deterioration.

Conditionally suitable trees

Trees exhibiting localized internal abnormalities, minor cavities, pruning wounds, fungal activity, or early signs of deterioration may be retained where their heritage significance warrants continued conservation. Appropriate arboricultural measures, including scientifically justified pruning, management of fungal problems, protection from avoidable mechanical injury, and periodic reassessment, should be undertaken. Repeat ERT can be particularly useful for monitoring trees where progressive internal deterioration is suspected.

Not suitable for immediate designation

Trees exhibiting extensive cavities, advanced decay, substantial loss of sound wood, severe cankers, or major structural discontinuities should undergo detailed structural and tree-risk assessment before a final management decision is made. Where the tree has exceptional cultural or historical significance, feasible risk-reduction or stabilization measures should be evaluated before removal is considered.

The integration of VTA and ERT therefore provides a stronger basis for distinguishing superficial or localized defects from structurally significant internal deterioration. This approach can help minimize unnecessary removal of valuable heritage trees while simultaneously identifying trees that may present increasing structural risks and require timely intervention.

However, ERT should not be interpreted as a direct measurement of mechanical strength or probability of tree failure. Electrical resistivity is affected by several interacting factors, including wood moisture, electrolyte concentration, temperature, wood density, anatomy, water status, and species-specific characteristics. Bär et al. (2019) demonstrated substantial interspecific, intraspecific, and within-tree variation in ER tomograms and emphasized the importance of reference measurements for reliable interpretation.

Similarly, Ganthaler et al. (2019) demonstrated that temperature, tree water status, bark characteristics, and electrode installation can influence electrical resistance measurements. Their findings indicate that environmental and measurement conditions need to be considered when interpreting absolute resistivity values and comparing measurements among trees or between different assessment periods.

Accordingly, the present study supports the interpretation of ERT primarily as a diagnostic and decision-support technique rather than a stand-alone tree-risk assessment method. Its greatest value lies in providing additional evidence about the internal distribution of wood conditions, which can then be interpreted together with VTA observations, tree biology, site conditions, and professional arboricultural judgement. The combined VTA–ERT approach consequently provides a more comprehensive and scientifically defensible basis for heritage-tree conservation, monitoring, and long-term management.

4. Conclusions

The present investigation concludes that the integration of Visual Tree Assessment (VTA) and Electrical Resistance Tomography (ERT) provides a more comprehensive and reliable approach for assessing heritage trees than either technique used independently. VTA effectively identifies visible defects, tree architecture, site conditions, and potential risk factors, while ERT provides additional information on concealed internal structural conditions.

Most of the assessed trees exhibited continuous and well-developed heartwood, indicating good internal structural continuity and supporting their continued conservation. Although localized low-resistivity and moisture-rich regions were observed in some trees, these areas did not necessarily indicate advanced decay or immediate structural failure. This confirms that ERT results should be interpreted in relation to the overall tomographic pattern and other tree characteristics rather than on the basis of resistivity values alone.

ERT successfully identified trees showing extensive cavities, advanced deterioration, moisture-rich regions, and reduced sound wood, thereby providing important information that was not always evident

from external inspection. The technique was particularly useful for detecting concealed internal abnormalities in trees that appeared relatively healthy externally.

The study also confirms that external appearance and tree age alone are not sufficient criteria for determining the structural condition or conservation status of heritage trees. Trees with prominent external wounds or pruning injuries may retain substantial internal sound wood, whereas trees with limited visible symptoms may contain significant internal deterioration. Therefore, conservation and management decisions should be based on an integrated evaluation of external defects, internal structural condition, tree architecture, site exposure, defect progression, and heritage significance.

The findings demonstrate that ERT should be regarded as a complementary diagnostic tool rather than a replacement for professional arboricultural assessment. Its greatest value lies in providing additional information on internal stem condition and reducing uncertainty associated with concealed defects. When combined with VTA and other appropriate diagnostic observations, ERT can strengthen the scientific basis of tree-risk assessment and management decisions.

Based on the integrated assessment, trees with sound internal structure and no major defects can be prioritized for heritage designation and routine monitoring. Trees showing localized internal abnormalities can be retained with appropriate arboricultural interventions and periodic reassessment, while trees exhibiting extensive decay, hollowness, or major structural deterioration should undergo detailed tree-risk assessment and appropriate risk-reduction measures.

Overall, the study confirms that the VTA–ERT integrated approach is valuable for evidence-based heritage-tree conservation and urban tree-risk management. Its application can help identify structurally sound trees, facilitate early detection of concealed deterioration, reduce unnecessary removal of valuable mature trees, and support timely intervention where genuine structural risks are present. The adoption of this integrated approach can therefore contribute to the long-term conservation of trees possessing important ecological, cultural, historical, and social values while maintaining public safety.

Recommendations

1. **Integrate ERT into Heritage Tree Assessment Protocols**: Electrical Resistance Tomography (ERT) should be incorporated as a complementary tool to Visual Tree Assessment (VTA) for evaluating the internal structural integrity of heritage trees. ERT provides objective information on heartwood continuity, internal decay, moisture distribution, and hidden structural defects that cannot be reliably detected through external visual inspection alone.
2. **Adopt Standardized Heritage Tree Classification Criteria**: Heritage tree designation should incorporate ERT-based internal structural assessment using the following classification framework:

- Suitable for Heritage Tree Designation: Trees exhibiting a continuous, well-defined heartwood core with no evidence of significant hollowness, decay, or structural weakness.

- Conditionally Suitable: Trees displaying localized moisture-rich zones, asymmetric or partially developed heartwood, or heterogeneous resistivity patterns without evidence of critical structural failure. These trees should remain under periodic monitoring.
- Not Suitable: Trees exhibiting extensive low-resistance inner cores indicative of advanced decay, internal hollowness, or severe structural deterioration should not receive unconditional heritage designation until appropriate risk mitigation measures are undertaken.

1. **Establish Periodic Monitoring Programmes**: Heritage and conditionally suitable trees should undergo periodic ERT reassessment at regular intervals (approximately every 2–5 years, depending on tree condition, species, age, and site risk). Repeat measurements at fixed stem heights will facilitate temporal comparison, early detection of structural deterioration, and evaluation of management interventions.
2. **Undertake Targeted Confirmatory Testing**: Where ERT identifies ambiguous resistivity patterns or extensive low-resistance zones, selective and minimally invasive increment coring or other confirmatory investigations should be conducted to validate internal conditions while minimizing damage to the tree.
3. **Integrate ERT into Comprehensive Urban Tree Risk Assessment**: ERT results should be interpreted alongside Visual Tree Assessment (VTA), crown condition, stem defects, tree lean, rooting condition, site characteristics, occupancy level, and public exposure to support science-based decisions regarding conservation, maintenance, pruning, risk mitigation, or public safety interventions while avoiding unnecessary tree removal.
4. **Implement Appropriate Conservation and Management Measures**: Trees exhibiting moisture-related internal anomalies should receive appropriate site-specific management, including improved soil drainage, soil aeration, wound management, reduction of mechanical stress, and regular health monitoring. Trees that are presently unsuitable for heritage designation may still be retained under protected conservation or intensive monitoring programmes following suitable risk mitigation.
5. **Develop Standardized National Guidelines and Digital Databases**: National, state, and municipal authorities should develop standardized protocols for ERT data acquisition, processing, interpretation, and decision-making. A centralized digital database containing ERT tomograms, dendrometric measurements, tree health records, geographic information, inspection history, and management actions should be established to facilitate long-term monitoring, change detection, and adaptive management of heritage trees.
6. **Promote Further Research and Technology Integration**: Future research should validate ERT across a broader range of tree species, age classes, climatic conditions, and stages of decay. Integration of ERT with complementary non-destructive techniques, including acoustic tomography, advanced imaging technologies, and predictive modelling approaches, is recommended to improve diagnostic accuracy, structural assessment, and long-term conservation planning.

These recommendations provide a scientifically robust framework for integrating non-destructive technologies into heritage tree evaluation, thereby enhancing the accuracy, transparency, and

sustainability of heritage tree conservation and urban forest management.

Declarations

Acknowledgement: The authors gratefully acknowledge the Director, Institute of Wood Science and Technology (ICFRE-IWST), and the Director, Institute of Forest Genetics and Tree Breeding (ICFRE-IFGTB), for providing the necessary facilities and support to conduct this study. The authors also sincerely thank the Tamil Nadu Forest Department, Government of Tamil Nadu, Chennai, for providing financial support for the project on the conservation and health assessment of heritage trees of Chennai. The authors are grateful to S. P. Subramani, taxonomist, for his valuable assistance in identifying the heritage trees included in this study.

Author contributions: All authors have approved the final version of the manuscript.

B.N.D. conceptualized, planned, and executed the fieldwork, and led the drafting of the manuscript.

C.B. assisted in data analysis, compilation, and contributed to the manuscript drafting by reviewing the manuscript and provided valuable suggestions for its improvement.

Competing interests: The authors declare that they have received no financial support for the preparation of this manuscript and have no competing interests to disclose.

Ethics approval: Not applicable. The study did not involve human participants, human data, or animals.

Consent to participate: Not applicable, as this study did not involve human participants.

Data availability: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Consent to Publish: Not applicable, as the study does not contain any personally identifiable information or individual-level data requiring consent for publication. All authors have read and approved the final manuscript and consent to its publication

Clinical trial number: Not Applicable

Funding information: No fund is available for publication of this manuscript

References

1. Bär A, Hamacher M, Ganthaler A, Losso A, Mayr S. (2019). Electrical resistivity tomography: Patterns in *Betula pendula*, *Fagus sylvatica*, *Picea abies* and *Pinus sylvestris*. *Tree Physiology*, 39(7), 1262–1271. https://doi.org/10.1093/treephys/tpz052
2. Berthier S, Kokutse AD, Stokes A, Fourcaud T. Irregular heartwood formation in maritime pine (*Pinus pinaster* Ait.): Consequences for biomechanical and hydraulic tree functioning. Ann Botany.

2001;87(1):19–25. https://doi.org/10.1006/anbo.2000.1290.

3. Bieker D, Rust S. Electric resistivity tomography shows radial variation of electrolytes in *Quercus robur*. Can J For Res. 2010a;40:1189–93. https://doi.org/10.1139/X10-076.
4. Bieker D, Rust S. Non-destructive estimation of sapwood and heartwood width in Scots pine (*Pinus sylvestris* L). Silva Fenn. 2010b;44:267–73. assessed on 12.07.2026). http://www.metla.fi/silvafennica/full/sf44/sf442267.pdf.
5. Bieker D, Kehr R, Weber G, Rust S. Non-destructive monitoring of early stages of white rot by *Trametes versicolor* in *Fraxinus excelsior*. Ann For Sci. 2010;67:210. https://doi.org/10.1051/forest/2009103.
6. Brazee NJ, Marra RE, Göcke L, Van Wassenaer P. Non-destructive assessment of internal decay in three hardwood species of northeastern North America using sonic and electrical impedance tomography. Forestry. 2011;84:33–9. https://doi.org/10.1093/forestry/cpq040.
7. Deflorio G, Fink S, Schwarze FWMR. Detection of incipient decay in tree stems using electrical resistance tomography. Wood Sci Technol. 2010;44:1–14.
8. Divakara BN, Singh MP. (2025). Application of Electric Resistance Tomograph (ERT): Innovative non-destructive method in analysing interiors of standing trees in tropics. *Can. J. For. Res.* 2015, *55*, 1–15. https://doi.org/10.1139/cjfr-2024-0311
9. Divakara BN, Nikitha CU, Chauhan SS. Deciphering interiors of commercially important Indian trees using 3D Electric Resistance Tomograph (ERT). Indian For. 2020;146:1149–53. https://doi.org/10.36808/if/2020/v146i12/156777.
10. Divakara BN, Chaithra S. Electric Resistance Tomograph (ERT): A review as non-destructive tool (NDT) in deciphering interiors of standing trees. Sens Imaging. 2022;23., Article 22. https://doi.org/10.1007/s11220-022-00385-3.
11. Ganthaler A, Sailer J, Bär A, Losso A, Mayr S. Non-invasive analysis of tree stems by electrical resistivity tomography: Unraveling the effects of temperature, water status, and electrode installation. Front Plant Sci. 2019;10:1455. https://doi.org/10.3389/fpls.2019.01455.
12. Guyot A, Ostergaard KT, Lenkopane M, Fan J, Lockington DA. Using electrical resistivity tomography to differentiate sapwood from heartwood: Application to conifers. Tree Physiol. 2013;33(2):187–94. https://doi.org/10.1093/treephys/tps128.
13. James KR, Haritos N, Ades PK. Mechanical stability of trees under dynamic loading. Trees. 2018;32:1–17.
14. Jim CY. Evaluation of heritage trees for conservation and management in Guangzhou city (China). Environ Manage. 2004;33(1):74–86. https://doi.org/10.1007/s00267-003-0169-0.
15. Lindenmayer DB, Blanchard W, McBurney L, Blair D, Banks S, Likens GE, Franklin JF, Laurance WF, Stein JAR, Gibbons P. Interacting factors driving a major loss of large trees with cavities in a forest ecosystem. PLoS ONE. 2012;7(10):e41864. https://doi.org/10.1371/journal.pone.0041864.
16. Mattheck C, Breloer H. Field guide for visual tree assessment (VTA). Arboricultural J. 1994;18(1):1–23. https://doi.org/10.1080/03071375.1994.9746995.

17. Nicolotti G, Socco LV, Martinis R, Godio A, Sambuelli L. Application and comparison of three tomographic techniques for detection of decay in trees. J Arboric. 2003;29(2):66–78. https://doi.org/10.48044/jauf.2003.009.
18. Roman LA, Pearsall H, Eisenman TS, Conway TM, Fahey RT, Landry SM, Vogt J, van Doorn NS, Grove JM, Locke DH, Bardekjian AC, Battles JJ, Cadenasso ML, van den Konijnendijk CC, Avolio M, Berland A, Jenerette GD, Mincey SK, Pataki DE, Staudhammer C. Human and biophysical legacies shape contemporary urban forests: A literature synthesis. Urban Forestry Urban Green. 2018;31:157–68. https://doi.org/10.1016/j.ufug.2018.03.004.
19. Shigo AL. A New Tree Biology: Facts, Photos, and Philosophies on Trees and Their Problems and Proper Care. Associates: Shigo and Trees; 1986.
20. Smiley ET, Matheny NP, Lilly S. Tree risk assessment. Routledge Handbook of Urban Forestry. International Society of Arboriculture. Routledge; 2017. pp. 478–88.
21. Stokes A, Berthier S. Irregular heartwood formation in *Pinus pinaster* Ait. is related to eccentric, radial, stem growth. For Ecol Manag. 2000;135(1–3):115–21. https://doi.org/10.1016/S0378-1127(00)00303-0.
22. Yue X, Wang L, Wacker JP, Zhu Z. Electric resistance tomography and stress wave tomography for decay detection in trees—a comparison study. PeerJ. 2019;7:e6444. https://doi.org/10.7717/peerj.6444.

Figures

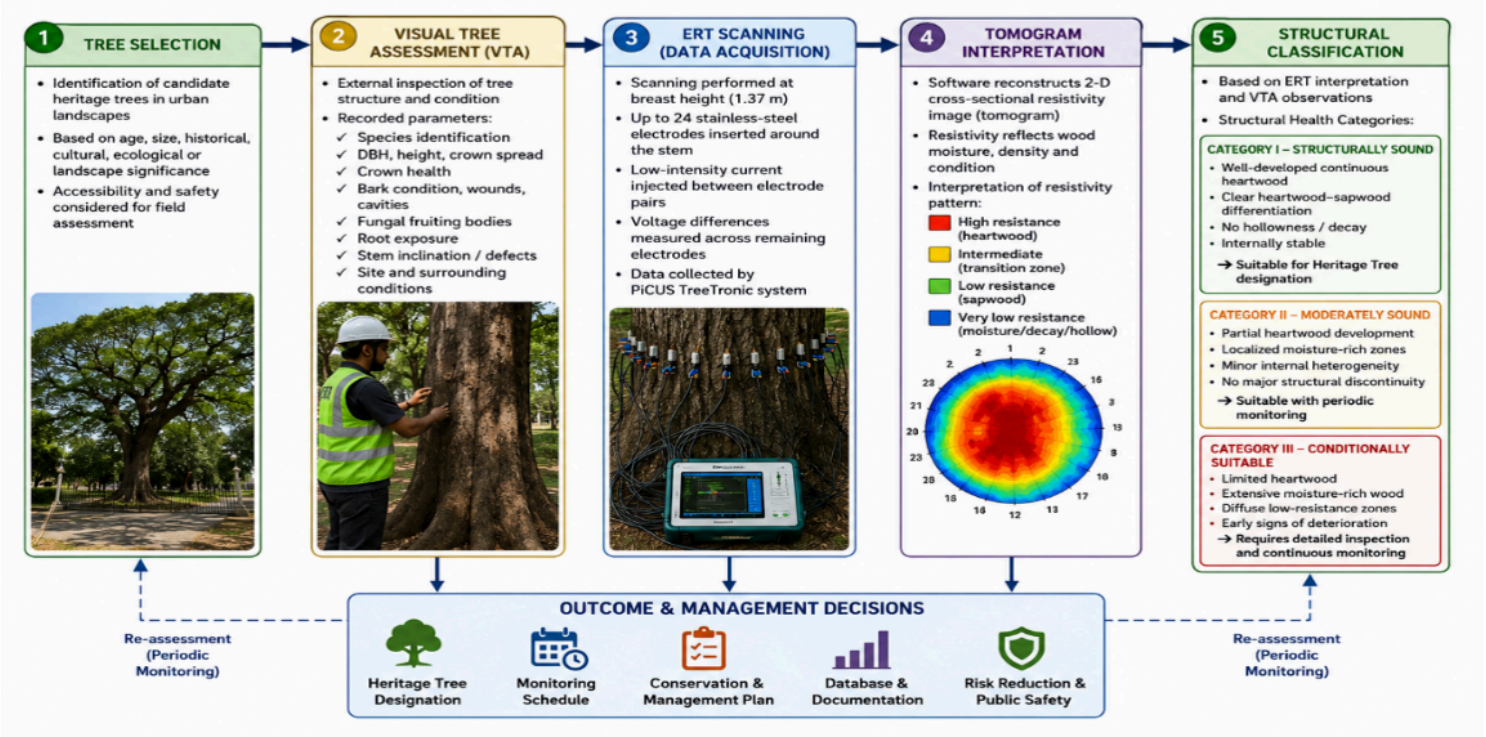


Figure 1

Electrical Resistance Tomography Workflow for Heritage Tree Assessment