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OPTICAL DIAGNOSTICS OF ATMOSPHERIC-PRESSURE PLASMA JETS: FROM EMISSION SPECTROSCOPY TO THREE-DIMENSIONAL IMAGING AND DATA ANALYSIS

Farah Wathiq Hadi *

Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq.

* Corresponding author; Email: farah.w@sc.uobaghdad.edu.iq

ORCID Details

Farah Wathiq Hadi: <https://orcid.org/0009-0003-7304-7811>

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ABSTRACT

Atmospheric-pressure plasma jets (APPJs) are strongly non-equilibrium plasma sources whose optical emission, reactive chemistry, gas dynamics, and propagation behavior can vary over short spatial and temporal scales. These features make optical diagnostics indispensable, but they also expose the limitations of conventional line-of-sight and time-averaged measurements. This review critically examines the progression of APPJ optical diagnostics from conventional optical emission spectroscopy (OES) to spatially and temporally resolved spectroscopy, fast and intensified imaging, schlieren visualization, hyperspectral imaging, tomographic reconstruction, and data-driven analysis. Particular emphasis is placed on the trade-offs among spectral, spatial, and temporal resolution and on the growing role of digital image processing and machine learning. Recent studies have shown that tomographic OES can recover three-dimensional emission distributions without imposing cylindrical symmetry, hyperspectral imaging can map wavelength-dependent emission across two spatial dimensions, and machine-learning approaches can extract process-related information from large spectral datasets. Persistent challenges include line-of-sight integration, limited standardization of preprocessing and reconstruction pipelines, calibration and synchronization burdens, reconstruction artifacts, and the uncertain transferability of machine-learning models across plasma sources. The review identifies the integration of spectroscopy, high-speed imaging, volumetric reconstruction, and physics-informed analysis as a promising route toward more interpretable APPJ characterization. Achieving reliable real-time operation will require further validation, calibration, and uncertainty assessment.

Keywords: Optical Emission Spectroscopy; Time-Gated Imaging; Schlieren Visualization; Hyperspectral Mapping; Tomographic Reconstruction; Machine Learning

1 INTRODUCTION

Atmospheric-pressure plasma jets (APPJs) deliver reactive species to targets in ambient air without a vacuum chamber. Applications include surface processing, thin-film deposition, environmental treatment, and plasma medicine [1,2]. Quantitative diagnosis is difficult because excitation, chemistry, gas transport, and target interaction occur together.

The behavior of an APPJ depends on the working-gas composition, gas flow rate, voltage waveform, pulse duration, repetition frequency, electrode geometry, surrounding atmosphere, and jet-to-target distance. Ambient nitrogen, oxygen, and water vapor can alter the reactive species and emission pattern. The visible plume may also contain rapidly propagating guided ionization waves rather than a stationary luminous column [2,3]. Therefore, diagnostic results depend on where and when the signal is collected.

Optical emission spectroscopy (OES) remains a central diagnostic technique because it is non-invasive, experimentally accessible, and provides information about the emitting species. Conventional OES, however, integrates light along a line of sight and, unless time-gated, over multiple discharge cycles. In a spatially non-uniform APPJ, this averaging can obscure local behavior [4]. Earlier reviews described the value of OES for APPJ characterization, including its sensitivity to impurities and gas mixing [4]. The range of available optical methods has since expanded.

Recent studies have increasingly combined spectral and imaging information. Fast and intensified camera imaging can resolve guided ionization wave propagation, schlieren methods reveal gas density gradients and mixing, electro-optic and Stark-based methods provide electric field information, hyperspectral systems map wavelength-dependent emission across two spatial dimensions, and optical tomography reconstructs three-dimensional emission structures [5,6,7,8,9,10]. Machine learning has also been investigated for dimensionality reduction, inference, and process monitoring using large optical datasets [11,12,13,14].

This review examines the development of APPJ diagnostics from conventional OES to methods with greater spatial, temporal, and spectral resolution. It compares the information provided by each method, the information lost through projection or averaging, and the experimental requirements for higher-dimensional measurements. It also considers where digital image processing and machine learning can improve the interpretation. The aim is to identify complementary methods that together provide a more complete description of APPJ behavior. Surface-treatment studies also motivate matching source conditions and diagnostic observables to the intended application [15].

2 SCOPE AND LITERATURE-SELECTION APPROACH

This article is a focused narrative review rather than a systematic review or meta-analysis. Relevant studies were identified through targeted searches of publisher platforms, bibliographic records, and reference lists. Search terms included atmospheric-pressure plasma jet, optical emission spectroscopy, time-resolved imaging, schlieren imaging, hyperspectral imaging, tomography, three-dimensional reconstruction, and machine learning. The search was not designed to identify all published studies. Priority was given to peer-reviewed work published between 2020 and 2026, while earlier studies were included when they established diagnostic concepts relevant to current APPJ research.

The studies are organized by the main type of information they provide: spectroscopic composition and inferred plasma parameters; temporal propagation; spatial morphology and gas flow; electric field structure; spatial and spectral mapping; three-dimensional reconstruction; and computational analysis. This organization allows comparison of what each method measures, the assumptions it requires, and its limitations.

3 APPJ PHYSICS AND DIAGNOSTIC REQUIREMENTS

APPJs are commonly operated using helium or argon. Molecular gases may be added deliberately, while ambient air can be mixed with the plasma effluent. As a result, the chemistry may vary along and across the jet. Studies of argon–water mixtures show that changes in the amount of added water can affect OH emission and temperatures inferred from the spectra [3]. Diagnostic geometry, the volume from which light is collected, and environmental conditions should therefore be reported and considered when interpreting measurements.

In many pulsed APPJs, the visible plume contains guided ionization waves, sometimes called plasma bullets. These waves propagate through processes involving electric fields, ionization, and transport, with dynamics on nanosecond to microsecond timescales [2]. Long camera exposures and slow spectral measurements can describe the average behavior but cannot resolve these rapid changes on their own.

An ideal diagnostic should identify emitting species, resolve local structures and fast events, and disturb the plasma as little as possible. No single method meets all these requirements equally well. Therefore, the selection of complementary methods depends on the physical question, acceptable uncertainty, and experimental complexity.

4 OPTICAL EMISSION SPECTROSCOPY

Optical emission spectroscopy (OES) is a widely used passive diagnostic technique for APPJs. Atomic lines and molecular bands indicate emissions from excited Ar, He, O, OH, N₂, and N₂⁺. When combined with suitable models and clearly

stated assumptions, the spectra may support estimates of the rotational, vibrational, and excitation temperatures, as well as other plasma parameters [4]. OES does not require the insertion of a probe into the plasma and can cover a broad wavelength range.

Spectral identification must be separated from quantitative inference. OES detects radiating excited states; it does not directly provide ground-state species densities. Rotational temperatures fitted from OH or N₂ bands are often used to estimate gas temperature, but the inferred value depends on the emitting molecule and its population distribution [4]. Agreement between a fitted spectrum and a model therefore needs checks on spectral resolution, detector response, and the adopted population assumptions.

Likewise, an excitation temperature derived from a Boltzmann plot should not automatically be identified with electron temperature in a non-equilibrium jet. A defensible comparison reports which lines or bands were fitted, the model used, the collection region, and the exposure interval. Conflicting temperature estimates may indicate different sampled regions or departures from the model assumptions rather than a physical contradiction [4].

Published studies have illustrated different uses of OES in atmospheric-pressure plasma jets. Mrotzek and Viöl examined spectroscopic changes in a jet used for cold plasma spraying [16]. Roomy et al. applied a Boltzmann-plot method to an argon jet and investigated the influence of gas flow on inferred plasma parameters [17]. Kadhim and Humud studied the relationship between the operating conditions and measured properties of an argon jet developed for biological applications [18]. Giannakaris et al. analyzed Ar I and Ar II emission from an industrial thermal plasma jet under different operating conditions [19]. This thermal system differs from the non-thermal jets discussed elsewhere in this review.

The measured spectrum is a spatially and temporally weighted signal, as outlined in the Introduction. Spatially restricted collection and time gating improve localization, but reduce the collected signal and increase alignment and synchronization requirements. Figure 1 contrasts single-view collection with multi-view reconstruction.

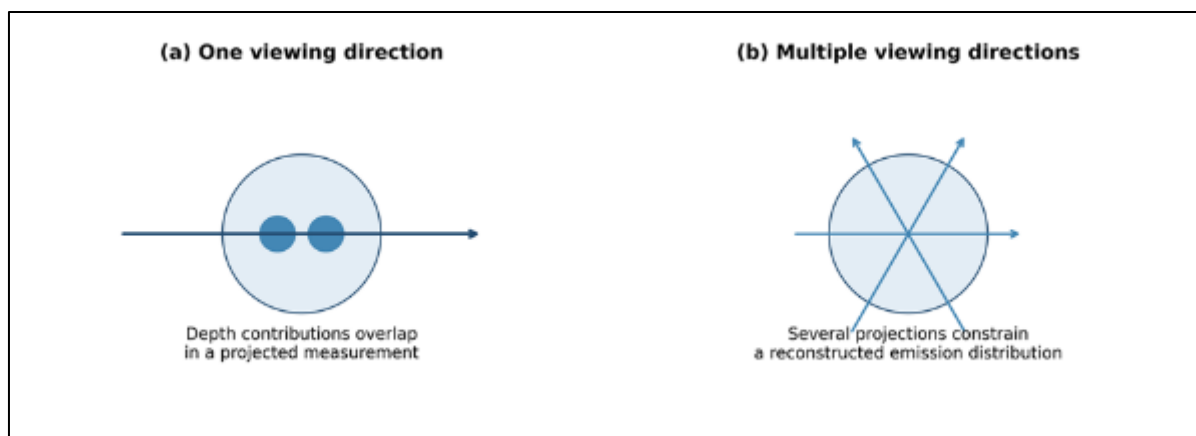


Figure 1: Conceptual comparison of a single projected measurement and multiple viewing directions used for emission reconstruction. The circles represent a cross-section of an emitting volume; three-dimensional reconstruction also requires sampling along the jet. Author-created schematic, not experimental data.

Space- and time-resolved OES can restrict the region and time interval from which light is collected. Lepikhin et al. combined these measurements with numerical simulation to distinguish the phases of a nanosecond nitrogen discharge studied at 200 mbar [20]. Stark-polarization spectroscopy has also been used to investigate the electric-field dynamics during guided ionization-wave propagation and plasma-surface interaction [21,22]. These examples show that OES results depend on the acquisition strategy and the assumptions used to interpret the spectra, as well as on the spectrometer.

5 FAST, TIME-RESOLVED, AND SCHLIEREN IMAGING

Fast imaging is useful when an APPJ plume contains rapidly propagating ionization fronts. High-speed and intensified charge-coupled device (ICCD) cameras can record short-lived phases. When discharges are sufficiently repeatable, images taken at different delays after the electrical pulse can reconstruct their time evolution. These measurements can reveal the propagation speed, plume shape, branching, and interactions with a target.

McDonnell et al. combined Stark-polarization spectroscopy, schlieren imaging, and fast two-dimensional emission imaging to study a helium APPJ [5]. These methods provided complementary information about the electric field, gas mixing, and visible plume. Changes in emission intensity may reflect gas mixing or electric-field dynamics and should not automatically be attributed to changes in species concentration. Time-resolved ICCD studies have also examined the propagation of initial ionization waves in helium jets [9]. A separate study of a nano-pulsed APPJ combined OES with electrical characterization to examine source operation and reactive-species production [23].

Schlieren imaging reveals refractive-index gradients associated with changes in gas density and temperature. Therefore, it can help visualize the working-gas flow, mixing with ambient air, and changes in flow behavior that emission images do not show directly. Traldi et al. reviewed the advantages and setup-dependent limitations of schlieren methods in atmospheric-plasma diagnostics [24]. Schlieren images should be interpreted alongside other measurements: a refractive-index gradient alone does not identify emitting species or uniquely determine gas temperature.

Fast and time-gated imaging can resolve the shape and motion of a plasma plume; however, an unfiltered image provides limited information about the species responsible for its emission. Combining imaging with OES or wavelength-selective filters can help relate the observed structures to particular emitters or excitation processes. The interpretation also depends on camera calibration, exposure timing, and detector sensitivity at the selected wavelengths. Table 1 summarizes the methods and evidence discussed above.

Table 1: Information content and limitations of major optical diagnostic approaches

Technique	Primary information	Spatial capability	Temporal capability	Main strength	Main limitation
Conventional OES	Emitting species and model-derived parameters	Depends on collection geometry	Time averaged unless gated	Non-invasive spectroscopy	Line-of-sight and time averaging
Time-resolved OES	Transient emission and inferred parameters	Depends on collection geometry	High with suitable gating	Separates discharge phases	Timing and signal requirements
High-speed/ICCD imaging	Projected plume shape and propagation	Two-dimensional projection	High	Captures rapid motion	Limited species specificity without filtering
Schlieren imaging	Refractive-index gradients related to gas flow	Two-dimensional projection	Depends on camera setup	Reveals gas mixing	Does not identify emitting species
Hyperspectral imaging	Spatially resolved emission spectra	Two-dimensional	System dependent	Combines spatial and spectral data	Calibration and data volume
Optical tomography / Tomo-OES	Reconstructed three-dimensional emission	Three-dimensional estimate	System dependent	Addresses projection overlap	Multiple views and reconstruction assumptions
Machine-learning analysis	Patterns and model-derived estimates	Inherited from input	System dependent	Analyzes large datasets	Training-domain dependence and validation

6 ELECTRIC-FIELD DIAGNOSTICS AS A COMPLEMENT TO EMISSION IMAGING

Emission intensity alone cannot reliably determine the electric field strength in an APPJ. Stark-polarization spectroscopy has been used to investigate electric field components in helium jets, including field enhancement near a surface during ionization-wave propagation [22]. Electro-optic probes provide another means to measure spatial and temporal changes in the field. Aljammal et al. examined the capabilities and practical limitations of such a probe for guided ionization waves in a cold helium APPJ [6]. These measurements complement emission imaging by providing information about the field involved in discharge propagation.

Electric-field measurements can help interpret image sequences. A change in plume length or brightness may reflect the redistribution of the electric field rather than a change in gas composition alone. These methods have practical

limitations, including specialized calibration, sensitivity to measurement geometry, and restricted observation regions. Some Stark-based approaches also require suitable emission lines that can be resolved and analyzed reliably.

7 HYPERSPECTRAL IMAGING AND SPATIALLY RESOLVED SPECTROSCOPY

Hyperspectral imaging records a spectrum at each sampled image position, forming a spatial-spectral data cube (Figure 2). Different wavelength channels can reveal distinct emission patterns, while parameters such as electron temperature require a physical inference model [8,25]. Calibration and projection geometry remain part of that interpretation.

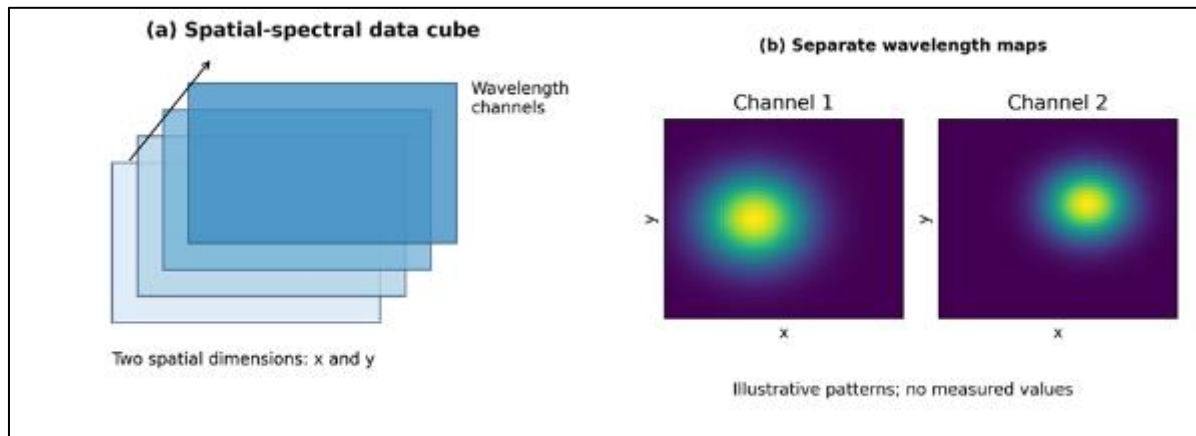


Figure 2: Conceptual hyperspectral data cube and separate wavelength-channel maps. The displayed patterns are illustrative and contain no measured plasma parameters. They show how spatial and spectral information are stored; parameter inference requires calibration and a physical model. Author-created schematic.

Khazem et al. used hyperspectral imaging to examine a microwave argon plasma jet expanding into ambient air [8]. In subsequent work, spectral images were analyzed with a collisional-radiative model to estimate two-dimensional distributions of electron temperature, electron density, and argon molecular-ion density [25]. These values are model-derived estimates, not quantities measured directly by the camera. These studies illustrate how spatially resolved spectra can provide more detail than a single spectrum, while increasing the need for calibration and model validation.

Hyperspectral imaging produces large and complex datasets. Wavelength calibration, correction for uneven detector response, image alignment, background removal, and spectral fitting all affect the resulting map. Uncertainties in these steps must be considered when interpreting model-derived parameters. Acquisition speed may also limit the study of events that cannot be reliably reproduced. Thus, hyperspectral imaging provides richer spatial and spectral information but requires more careful data processing than conventional OES.

8 TOMOGRAPHIC AND THREE-DIMENSIONAL OPTICAL RECONSTRUCTION

APPJ images project a three-dimensional emitting volume onto a detector. The depth ambiguity is illustrated in Figure 1. Abel inversion can recover a radial profile when cylindrical symmetry is justified, whereas optical tomography uses multiple directions to constrain asymmetric emission [7]. Branched plumes, uneven mixing, and structured targets require particular care with symmetry assumptions.

Bentz reported the use of tomographic optical emission spectroscopy (Tomo-OES) for a nanosecond-pulsed atmospheric-pressure plasma jet and associated surface ionization waves [7]. By combining views from different directions, the study reconstructed three-dimensional distributions of emitted light without assuming cylindrical symmetry. This helps address the overlap of emission from separate locations in a single-view image. The reconstructed volume estimates light emission; it does not directly measure every plasma parameter in three dimensions.

Tomographic reconstruction introduces its own uncertainties. Camera positioning, the number and range of viewing angles, synchronization, detector response, image alignment, and the reconstruction algorithm can all affect the recovered volume. Limited viewing angles may produce artifacts, whereas smoothing during reconstruction can obscure small structures. Studies should report these choices and, where possible, test the reconstruction against independent measurements or simulated data with known structures.

The scientific value of APPJ tomography lies in resolving three-dimensional asymmetry that a projection image may conceal. The reconstructed emission can be compared spatially with spectroscopic results, electric-field measurements,

and the response of a treated surface. This is especially useful during jet–target interaction, when lateral spreading and off-axis structures may be difficult to distinguish in a single camera image. Such comparisons require measurements to be aligned in space and time.

9 DIGITAL IMAGE PROCESSING AND AI-ASSISTED PLASMA DIAGNOSTICS

Quantitative imaging depends on how raw data are processed. Background subtraction, noise reduction, correction for detector response, image alignment, segmentation, and geometric calibration can all affect the measured results. In tomography, processing errors may propagate into the reconstructed volume. In time-resolved imaging, they may bias estimates of plume length or propagation speed. Therefore, processing settings should be documented, and future measurements should assess how sensitive the results are to reasonable changes in those settings.

Machine learning adds another stage to data analysis. Bonzanini et al. reviewed supervised, unsupervised, and active-learning methods in low-temperature plasma research and discussed their use with optical, imaging, and electrical measurements [11]. Srikar et al. combined an argon collisional-radiative model with random-forest and deep-neural-network methods to accelerate electron-temperature estimation from spectroscopic data [12]. The performance of these methods depends on measurement quality, model assumptions, and the data used for training and testing.

Chen et al. analyzed approximately 96,000 spectra collected during atmospheric-pressure plasma-jet thin-film deposition. They used principal component analysis and supervised machine-learning models to investigate relationships between optical spectra and process-related quantities [13]. Tee et al. later studied interpolation-based data augmentation for predicting film thickness from OES data when labeled measurements were limited [14]. These examples show the potential of large spectral datasets, but a model trained on one device or operating range must be tested before being applied elsewhere. In the latter study, four augmentation cycles reduced the multilayer perceptron model's mean absolute error by 5.5% and mean absolute percentage error by 16.5% relative to its unaugmented baseline [14]. These are relative improvements in film-thickness prediction for that dataset, not accuracy measures for plasma temperature or a different jet.

Machine learning can reduce the dimensionality of complex datasets, accelerate parameter estimation, and identify patterns that are difficult to recognize manually. However, its predictions require physical validation. Changes in gas composition, applied voltage, jet geometry, optical alignment, or target material may cause new measurements to differ from the training data. Therefore, studies should describe how models were tested, quantify prediction uncertainty where possible, and avoid assuming that performance on one APPJ will transfer to another.

10 MULTIMODAL DIAGNOSTICS AND PLASMA-SURFACE INTERACTION

Table 2: Representative recent and foundational studies used in the comparative analysis

Study	System	Diagnostic approach	Principal contribution	Important limitation
Sarani et al. (2010) [3]	Ar / Ar-H ₂ O APPJ	OES + temperature analysis	Demonstrates strong sensitivity to water admixture	Line-integrated spectroscopy
Sretenović et al. (2011) [21]	He APPJ, bullet mode	Stark polarization spectroscopy	Electric-field distribution in guided ionization wave	Requires suitable emission and spectral fitting
McDonnell et al. (2022) [5]	He APPJ	Stark + schlieren + fast imaging	Integrated view of field, flow, and plume	Complex multimodal alignment
Mrotzek & Viöl (2022) [16]	APPJ for cold spraying	OES	Spectroscopic characterization under process conditions	No direct depth information
Lepikhin et al. (2023) [20]	N ₂ nanosecond discharge (200 mbar)	Space/time-resolved OES	Separates transient discharge phases	High synchronization burden
Aljammal et al. (2023) [6]	He cold APPJ	Electro-optic field probe	Resolved E-field diagnostics with explicit limits	Specialized probe and geometry

Bentz (2023) [7]	Nanosecond APPJ	Tomo-OES	3D emission without cylindrical symmetry	Multi-view reconstruction complexity
Roomy et al. (2023) [17]	Ar APPJ	OES + Boltzmann plot	Flow dependence of inferred parameters	Model-assumption dependence
Chen et al. (2024) [13]	APPJ thin-film deposition	OES + PCA + supervised ML	Large-scale spectral process monitoring	Model transferability
Srikar et al. (2024) [12]	Non-thermal Ar APPJ	OES + CR model + RF/DNN	Accelerated electron-temperature prediction	Dependent on model/training domain
Khazem et al. (2024) [8]	Microwave Ar jet	Hyperspectral imaging	Spatial-spectral mapping	Large data and calibration burden
Giannakaris et al. (2025) [10]	Industrial Ar APPJ	OES + LIBS imaging	Relates emission to surface-cleaning analysis	Application-specific setup
Khazem et al. (2026) [25]	Microwave Ar jet	Hyperspectral imaging + CR model	Model-derived 2D parameter maps	Model/calibration dependence
Tee et al. (2026) [14]	APPJ deposition	OES + PCA + data augmentation	Addresses sparse labels for film-thickness regression	Manufacturing-specific training data

Combining diagnostic methods is particularly useful when a plasma jet interacts with a surface. Electric fields, gas mixing, optical emission, and target conditions may change simultaneously, making a single measurement difficult to interpret. Mirzaee et al. investigated the spatial and temporal changes in the electric field as a helium APPJ reached a substrate and reported strong field enhancement near the interface [22]. Such measurements can help interpret changes observed in emission images during plasma–surface interactions.

Giannakaris et al. combined optical emission spectroscopy (OES) with laser-induced breakdown spectroscopy (LIBS) imaging to examine atmospheric-pressure plasma-jet surface cleaning [10]. OES provided information about the emitting plasma, whereas LIBS imaging provided spatially resolved information about the treated surface. Together, these measurements can help relate plasma operating conditions to treatment outcomes. This application-specific example should be distinguished from studies of non-thermal jets used for other purposes.

Operating conditions are essential when comparing results from different APPJ studies. Jet geometry, gas composition, voltage settings, target distance, and diagnostic method can all influence the measurement [15]. Therefore, a reported spectrum or image should include sufficient information about the source and measurement conditions to allow interpretation and comparison with other studies. Table 2 summarizes the methods and evidence discussed above.

11 RESEARCH GAPS

Line-of-sight OES and two-dimensional emission images are widely used in APPJ research, even when the emitting structure may be asymmetric and three-dimensional. These measurements are useful, but projection can conceal features at different depths. Volumetric methods can help address this limitation. Reports of reconstructed images should include viewing geometry, reconstruction assumptions, and uncertainty so that the apparent structures can be assessed critically.

Another gap is the limited direct comparison of different diagnostics under the same operating conditions. Measurements made on separate devices or at different gas flows and voltage settings cannot always be treated as descriptions of the same plasma state. Studies combining spectroscopy, imaging, and electric-field or gas-flow measurements on one jet could help distinguish physical differences from those caused by diagnostic assumptions.

Data-processing and reconstruction procedures are not always reported consistently across studies. Choices in background subtraction, noise reduction, image segmentation and alignment, calibration, reconstruction settings, and spectral fitting can affect quantitative results. If these choices are not described clearly, other researchers may be unable to reproduce or assess the analysis. Reporting processing steps and testing how sensitive the results are to key settings would improve comparability.

A central integration challenge is simultaneous chemical specificity, depth resolution, and fast timing. Signal strength, calibration, and synchronization constrain what can be acquired in one experiment.

Another limitation is the transfer of machine-learning models between plasma sources. A model trained on one jet geometry, gas mixture, voltage waveform, target, or optical system may perform differently when these conditions change. Testing on independent devices and operating conditions is required before claiming broad generalization. Reporting the training range and validation conditions would allow readers to assess such claims.

Comparing image processing, tomographic, and machine learning methods is difficult when they are tested on different datasets. Public APPJ imaging and spectroscopy datasets with calibration information and clearly defined evaluation tasks would support more meaningful comparisons. Shared datasets could also reveal when a method's apparent accuracy depends on a particular camera, plasma source, or processing pipeline.

12 FUTURE DIRECTIONS

Future APPJ studies should combine time-gated spectroscopy, fast imaging, hyperspectral measurements, electric field diagnostics, and three-dimensional reconstruction in synchronized experiments. Together, these methods may provide a more complete account of the emission, gas mixing, discharge propagation, and target interaction. Their integration requires careful timing, calibration across instruments and uncertainty assessment. The addition of instruments alone does not guarantee more accurate results.

Faster analysis is another research direction. Reduced physical models and machine-learning methods may transform optical measurements into rapid estimates of the plasma state. Once validated, these estimates could support feedback control of voltage, gas flow, pulse duration, or jet-to-target distance. Such applications require estimates of prediction uncertainty and testing under operating conditions beyond those used to train the model.

Tomography may become more practical if reliable reconstructions can be obtained from fewer viewing directions. Sparse-view reconstruction, compressed sensing, and methods guided by physical models are possible approaches. Fewer cameras or views could simplify experiments and increase the acquisition speed; however, they may also make the reconstruction less certain. The proposed methods should be tested on asymmetric structures and assessed for artifacts and uncertainty before use with rapidly changing APPJs.

Combining machine learning with physical models is another promising research direction. Collisional-radiative, fluid, or kinetic models can constrain predictions made from optical data. This may improve interpretability and reduce implausible results, although the physical models introduce assumptions and possible errors of their own. Both the data-driven method and its physical constraints require validation for the plasma sources and operating conditions under study.

Reproducibility requires publication of acquisition and processing settings, uncertainty estimates, and, where feasible, data and analysis code.

13 COMPARATIVE DISCUSSION

The methods discussed in this review provide different types of information on the same topic. Conventional OES provides spectral information but often averages over position and time. Time-gated spectroscopy resolves changes during discharge, whereas spatially resolved collection restricts the light collected to a selected region. Fast imaging records the plume shape and propagation, hyperspectral imaging combines spatial and spectral information, and tomography estimates the three-dimensional light emission. Each method provides information while introducing specific measurement and analysis requirements.

Table 1 summarizes why diagnostic selection must follow the physical question: front propagation, spectral identity, spatial mapping, and depth recovery demand different measurements. Instrument choice should therefore be tied to an observable and an uncertainty target.

These methods are most informative when their measurements can be compared under matched operating conditions. Spectroscopy, fast imaging, gas-flow visualization, electric-field measurements, and tomography provide complementary views of a plasma jet. Together, they may help determine whether an observed change is associated with chemistry, gas mixing, electric-field behavior, plume geometry, or target interaction. Agreement between methods can strengthen the interpretation, whereas disagreement can expose assumptions that require further testing.

Machine learning should be evaluated within the same physical framework as other diagnostic tools. It may help reduce data dimensionality, accelerate parameter estimation, detect unusual behavior, and support image reconstruction. When a model output is presented as a diagnostic result, the supporting calibrated measurements, validation methods, and prediction uncertainties should be reported. This is especially important when the model is applied outside its training conditions.

14 CONCLUSIONS

Optical diagnostics of atmospheric-pressure plasma jets have evolved from mainly line-of-sight and time-averaged measurements to methods that resolve spatial, temporal, spectral, and three-dimensional features. OES remains useful because it is accessible and provides spectral information, but its results require careful interpretation. Light collected along one viewing path may come from different plasma regions, while time averaging can conceal rapid events. Gas mixing and the assumptions used to infer plasma parameters must also be considered.

Fast and time-gated imaging can reveal short-lived ionization wave dynamics, whereas schlieren imaging provides information about gas density gradients and mixing. Electric field diagnostics help investigate the role of the field in discharge propagation. Hyperspectral imaging combines spatial and spectral measurements, and tomographic methods can estimate three-dimensional light emissions without requiring cylindrical symmetry. Image processing and machine learning can assist with the resulting datasets, provided that their outputs are validated and their uncertainties are assessed.

The central conclusion of this review is that APPJ diagnostics benefit from the combination of methods that measure different aspects of the same discharge. Synchronized spectroscopy, imaging, field measurements, and volumetric reconstruction may provide a more complete account of the emission, propagation, gas mixing, and target interaction. Progress depends on reliable calibration, transparent data processing, uncertainty assessments, and validation across different plasma sources. These steps are particularly important before the diagnostic results are used to guide real-time processes.

This narrative review synthesizes published studies; no new measurements or data sets are reported.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Declarations: Use of AI-assisted tools

OpenAI ChatGPT assisted with literature organization, drafting and editing of the comparative discussion, language editing, and document formatting. The author is responsible for the scientific content, interpretations, and citations.

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