

Original Research

Tungsten (VI) Oxide Nanoparticles: Green Synthesis Using *Petroselinum crispum* Leaf Extract, Structural Characterization, and Gas Sensing Performance

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Abstract

Background: WO₃ nanoparticles synthesized in a green way using plant materials are expected to exhibit unique properties controlled by the synergistic effects of the metal and plant constituents. **Methods:** *Petroselinum crispum* (parsley) leaf extract was used as a natural and renewable reducing and capping agent for the synthesis of WO₃ nanoparticles. **Results:** X-ray diffraction analysis revealed that the WO₃ nanoparticles had a monoclinic crystal structure with an average crystallite size of 20.3 nm, while energy-dispersive X-ray spectroscopy confirmed their high purity, and field-emission scanning electron microscopy revealed a rod-like morphology and controlled size distribution. The Raman spectrum of the nanoparticles showed strong peaks at 709 and 334 cm⁻¹, confirming their monoclinic structure. The optical bandgap was calculated as 2.89 eV using ultraviolet–visible spectroscopy. **Conclusions:** The WO₃ nanoparticles showed acceptable NO₂ and NH₃ sensing performances and exhibited optimal sensitivity at 100 and 200 °C, respectively, thus holding promise for gas sensor applications.

Keywords: WO₃; green synthesis; *Petroselinum crispum*; gas sensor; structural properties

1. Introduction

In recent years, nanoparticle research has accelerated due to its many applications. Moreover, the advancement of nanotechnology has profoundly influenced materials engineering by providing the potential to enhance and expand applications through the production of superior materials [1]. A particle of matter having a dimension ranging from one to one hundred nanometers (nm) is typically designated as a nanoparticle or ultrafine particle. Nanoparticles often display unique size-dependent characteristics, mostly due to their diminutive dimensions and extensive surface area [2]. The importance of metal nanoparticles arises from their nanoscale dimensions and elevated surface atom ratio, leading to substantial surface areas. The properties of particles at this minuscule size significantly diverge from those of their macroscopic counterparts [1]. Nanoparticles possess substantial applications across several industries, including environmental science, agriculture, food technology, biotechnology, and biomedicine, including wastewater treatment, environmental monitoring, functional food additives, and antimicrobial agents [2].

Semiconducting metal oxides are viable choices for gas sensing applications due to their high sensitivity to many target gases coupled with facile production methods, low cost, and excellent compatibility with other components and processes [3]. In recent decades, metal oxide semiconductors (MOS) have garnered increased attention

across numerous applications and sectors owing to their superior sensing properties, thermal stability, availability, and simplicity of synthesis. They are dependable and precise for the measurement and monitoring of environmentally significant hazardous gases, including NO₂, NO, N₂O, H₂S, CO, NH₃, CH₄, SO₂, and CO₂. MOS sensors are lightweight, cost-effective, and durable and exhibit great material sensitivity with rapid response times compared to other sensing technologies [4].

WO₃, among many transition-metal oxides, has an extensive array of advantageous qualities, such as significant structural flexibility, tunable optical characteristics, catalytic activity, electrochromism, and gas-sensing capabilities [3]. Tungsten trioxide (WO₃) is a wide bandgap transition metal oxide semiconductor that demonstrates a diverse array of innovative features beneficial for modern technological applications. WO₃ is a naturally occurring oxide that exhibits low toxicity to living organisms and is ecologically friendly; it is chemically stable throughout a broad temperature range and possesses distinctive electrical and optical characteristics [5]. Tungsten oxide nanoparticles (WO₃ NPs) have emerged as a promising material owing to their superior chemical stability, optical characteristics and catalytic efficacy. These nanoparticles have exceptional photochromic, electrochromic, and gas-sensing properties, rendering them very advantageous for energy storage, sensing and photocatalytic applications [6]. Recent studies have further demonstrated that structural optimiza-



tion and elemental incorporation in WO₃ nanostructures remarkably enhance their tunable optical bandgap and structural stability paving the way for highly efficient environmental remediation, including the advanced photocatalytic degradation of organic pollutants [7].

Conventional techniques for producing tungsten oxide nanoparticles, such as sol-gel processing, hydrothermal synthesis, and chemical vapor deposition have conventionally been employed in nanoparticle manufacturing [8]. However, a comprehensive comparison reveals that these physical and chemical methods suffer from significant drawbacks. They typically require elevated temperatures, high pressures, and complex equipment [9]. Moreover, they depend significantly on costly and dangerous chemicals, including toxic organic solvents and synthetic reducing or capping agents, which require substantial energy, produce toxic byproducts and pose serious dangers to the environment, cellular health and carcinogenicity [10]. Conversely, green synthesis has arisen as a better, environmentally friendly, cost-effective, and sustainable alternative [11]. This biological method employs natural resources, hence obviating the necessity for hazardous chemicals by utilizing biological molecules that function as both reducing and stabilizing agents. In contrast to conventional techniques, green synthesis functions at or near ambient conditions, markedly decreases production costs, eliminates hazardous waste generation, and produces very pure and biocompatible nanoparticles [12]. Among biological sources, plant-mediated synthesis is the most favored approach; in contrast to microbial approaches, it does not need intricate isolation culture growth or maintenance protocols, rendering it more rapid, economically efficient and simpler to scale for mass production [11].

Numerous studies have documented the effective green production of tungsten oxide (WO₃) nanostructures via plant extracts. *Psidium guajava* leaf extract was utilized as a reducing agent to synthesize WO₃ nanorods by a straightforward and environmentally benign approach [13]. In a separate work, *Cassia fistula* leaf extract was employed for the eco-friendly production of WO₃ nanoparticles [6]. Gas sensors utilizing semiconducting metal oxides are among the most prevalent devices for gas detection in residential, commercial, and industrial settings. They have several benefits, including affordability, simplicity of manufacturing, and compact dimensions [14]. Therefore, the use of environmentally sustainable synthesis methods in the advancement of chemiresistive gas sensors has garnered significant interest [15].

This research introduces an original green fabrication strategy for tungsten oxide (WO₃) nanoparticles, utilizing parsley (*Petroselinum crispum*) leaf extract as a sustainable bio-reducing and capping agent. Previous studies have utilized various plant extracts, including *Psidium guajava* and *Cassia fistula*, for WO₃ synthesis; however, the distinct phytochemical composition of parsley extract effec-

tively governs the growth of WO₃ into a precisely controlled rod-like morphology with superior surface characteristics, thereby differentiating it from nanoparticles synthesized through alternative biological methods.

Moreover, these customized structural attributes facilitate the examination of dual-gas sensing efficacy, whereby the produced WO₃ nanoparticles are methodically assessed for the detection of both oxidizing (NO₂) and reducing (NH₃) toxic gases at different operating temperatures. The thorough evaluation of sensitivity, response and recovery times bolstered by extensive structural and morphological characterization highlights a groundbreaking advancement in the creation of cost-effective and sustainable gas-sensing systems. In summary, the primary aim of this study is to synthesize WO₃ nanoparticles via an eco-friendly green route using parsley extract and to comprehensively evaluate their structural properties and dual-gas sensing performance towards NO₂ and NH₃.

2. Materials and Methods

2.1 Preparation of the Plant Extract

Initially, fresh parsley (*Petroselinum crispum*) leaves were collected from the market. Any dust or dirt adhering to the leaves was removed by thoroughly washing them several times with deionized water. Subsequent to this procedure, the leaves were desiccated in the shade for 10 days at ambient temperature, ensuring they were shielded from direct sunlight. Once fully dried the leaves were ground into a fine powder [5,16]. To prepare the plant extract 25 g of the powdered leaves were mixed with 500 mL of DW [5]. This mixture was then left at room temperature and protected from light for 24 hours [6]. To eliminate any impurities, the solution was filtered using filter paper, and the resulting extract was subsequently prepared for material synthesis.

2.2 Preparation of Pure Tungsten Oxide (NPs)

Added 8.3 g of sodium tungstate (Na₂WO₄·2H₂O, Sinopharm Chemical Reagent, Shanghai, China) to 50 mL of the extract from the plant, the resulting mixture was placed on a magnetic stirrer (Mtops Ms300hs, Misung Scientific, Yangju-si, South Korea) at 25 °C with a stirring speed of 600 rpm. During this mixing phase, critical biochemical interactions occur between the tungsten precursor and the green extract. The parsley extract contains phytochemicals including polyphenols and flavonoids which have electron-rich functional groups such as hydroxyls. These bioactive compounds engage with tungstate ions through electrostatic interactions and coordinate bonding. This complexation serves as a dynamic capping and stabilizing mechanism that restricts uncontrolled particle aggregation and directs subsequent crystal growth towards a certain rod-like morphology. Then, 3 mL of nitric acid (HNO₃, Central Drug House (P) Ltd, New Delhi, India) was added to the mixture to adjust the pH to 3, which led to an increase in the solution's viscosity. The mixture was then sub-

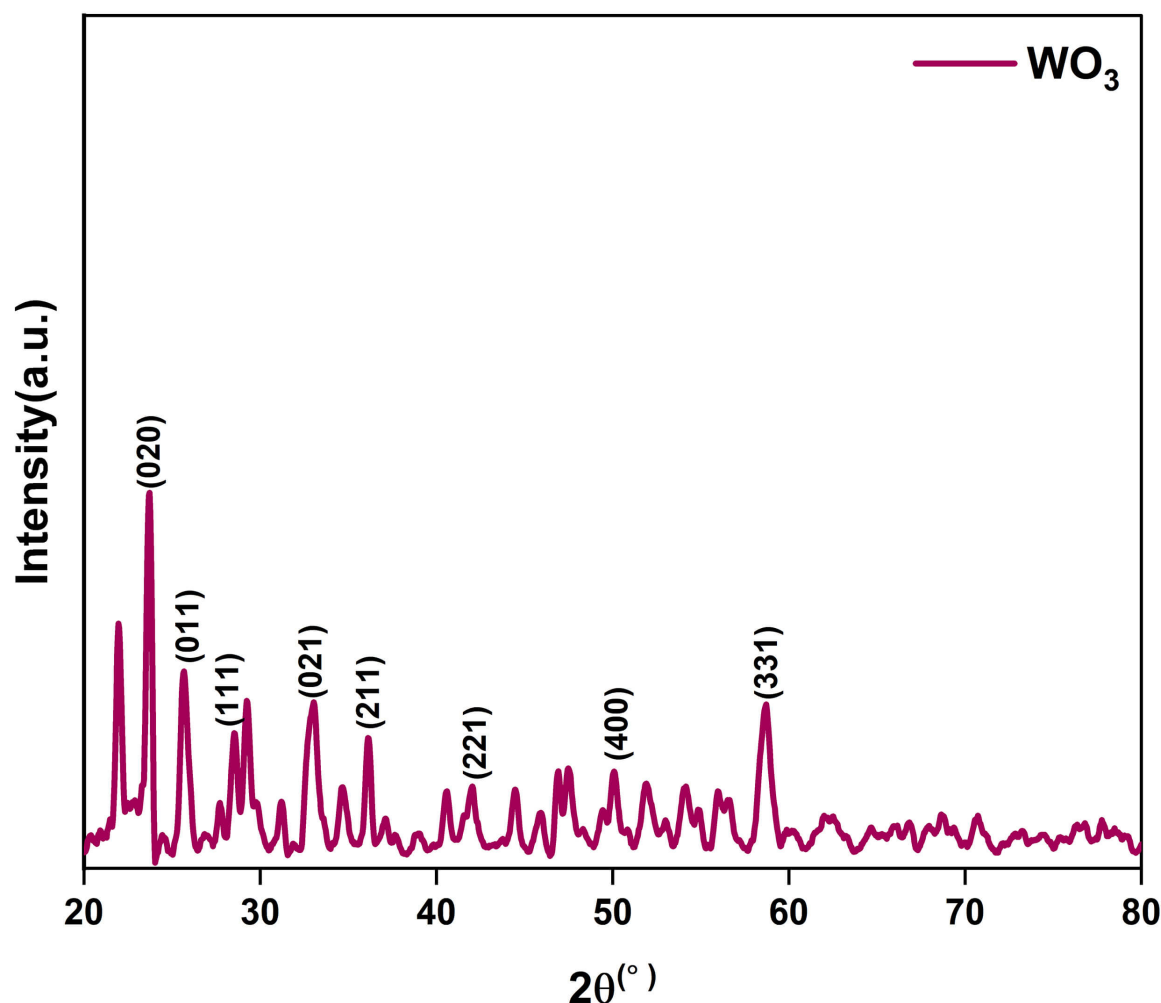


Fig. 1. X-ray Diffraction pattern of WO_3 .

jected to ultrasonic treatment (Model 031S, 40 kHz, Sky-men, Shenzhen, China) for 15 minutes. Following this, the solution was washed three times with distilled water using a centrifuge. It was then placed back on a magnetic stirrer at 75 °C for 3 hours until it completely dried and turned pale yellow in color. The dried material was ground using a mortar and then calcined in a furnace (Shin Saeng Scientific, Model SEF-201, Paju-si, South Korea) at 550 °C for 2 hours. Afterwards, it was allowed to cool gradually for 4 hours, and finally, it was ground again to obtain tungsten oxide nanoparticles. The plentiful phytochemicals in the plant extract enabled an effective reduction of the precursor yielding a significant and high-purity output. This illustrates the remarkable scalability and economic efficiency of our green synthesis technique.

3. Results

3.1 X-ray Diffraction (XRD) Analysis

The crystal structure of the green-synthesized tungsten oxide (WO_3) nanoparticles was investigated using X-ray diffraction (XRD, Rigaku Ultima IV, Tokyo, Japan).

The obtained diffraction pattern, shown in Fig. 1, revealed the presence of several well-defined diffraction peaks, indicating the crystalline nature of the prepared material. Significant diffraction peaks were at 2θ values of about 23.6° (020), 25.6° (011), 28.5° (111), 32.8° (021), 36.1° (211), 42.04° (221), 50° (400), and 58.6° (331). These peaks are characteristic of the monoclinic phase of tungsten trioxide (WO_3), and the diffraction pattern aligns well with the standard Joint Committee on Powder Diffraction Standards (JCPDS) card No. 01-075-2072 for monoclinic WO_3 . No secondary or impurity phases were detected [17]. The average crystallite size of the WO_3 nanoparticles was calculated using the Scherrer equation, focusing on the most intense diffraction peak. The determined crystallite size was about 20.3 nm, as detailed in Table 1. In addition, the micro-strain (ϵ) and dislocation density (δ) were calculated to assess the crystal lattice imperfections using the standard relations $\epsilon = \beta \cos \theta / 4$ and $\delta = 1 / D^2$, respectively. Furthermore, the internal tensile stress (σ) was evaluated using $\sigma = \epsilon \times Y$, where Y is the Young's modulus. The estimated average dislocation density was 3.695×10^{15} lines/m², along with a

Table 1. X-ray Diffraction parameters and crystallite size assessment.

2 theta (degree)	hkl	FWHM (deg)	theta (rad)	FWHM (rad)	D (nm)	Strain (ϵ) $\times 10^{-3}$	Stress (σ) GPa	$\delta \times 10^{15}$ (lines/m ²)	Matched by
23.661	020	0.472	0.206	0.008	17.196	2.016	0.605	3.382	
25.628	011	0.315	0.224	0.005	25.864	1.340	0.402	1.495	
28.543	111	0.315	0.249	0.005	26.023	1.332	0.400	1.477	
32.897	021	0.787	0.287	0.014	10.525	3.293	0.988	9.027	
36.108	211	0.472	0.315	0.008	17.703	1.958	0.587	3.191	01-075-2072
42.046	221	0.630	0.367	0.011	13.509	2.566	0.770	5.479	
50.066	400	0.236	0.437	0.004	37.152	0.933	0.280	0.724	
58.627	331	0.630	0.512	0.011	14.462	2.397	0.719	4.781	
Mean crystallite size					20.304	1.979	0.594	3.695	

FWHM, full width at half maximum.

corresponding mean micro-strain of 1.979×10^{-3} and stress of 0.594 GPa.

3.2 FE-SEM Analysis

The surface morphological and microstructural characteristics of the green-synthesized tungsten oxide nanoparticles were examined using scanning electron microscopy (SEM, ZEISS Sigma VP, Oberkochen, Germany). Fig. 2 shows the morphology of the WO₃ nanostructures at various SEM magnifications. The SEM images indicate that the green-synthesized samples comprise rod-like nanoparticles with a rather uniform distribution and some aggregation.

3.3 EDX Elemental Analysis

Energy-dispersive X-ray spectroscopy (EDX, Oxford Instruments, Wiesbaden, Germany) was utilized to determine the specific elemental composition of the green-synthesized WO₃ nanoparticles as shown in Fig. 3. The obtained spectrum explicitly exhibits the fundamental characteristic peaks for tungsten (W) and oxygen (O). Quantitative investigation indicated a tungsten content of 52.76 wt% (9.46 at%) and an oxygen content of 19.29 wt% (39.74 at%). In addition, modest peaks associated with nitrogen and sodium were seen in the analyzed samples. Aluminum and fluorine residues were also detected. There is a little peak at around 2.2 keV that corresponds to gold (Au).

3.4 UV-Vis Spectroscopy

Ultraviolet-visible (UV-Vis) spectroscopy (Shimadzu UV-1900i, Kyoto, Japan) was utilized to examine the optical properties of the produced particles. Fig. 4a illustrates that the absorption spectrum demonstrates significant absorption throughout a wide wavelength range in the UV area with a distinct absorption peak at around (278 nm). A progressive decline in absorbance within the visible spectrum was observed. In Fig. 4b, the optical band gap energy of the WO₃ nanoparticles was determined using the Tauc method, which revealed a distinct linear area around the absorption edge. Extrapolating this linear segment to the photon energy axis yielded an indirect band gap estimate of roughly (2.89 eV).

3.5 Photoluminescence Spectroscopy

Fig. 5 displays the photoluminescence (PL) spectrum (Model G9800A, Agilent Cary Eclipse, Santa Clara, CA, USA) operated via Cary WinFLR software (version 1.2, Agilent Technologies, Santa Clara, CA, USA) of green-synthesised WO₃ nanoparticles (350–900 nm), which has multi-band emission characteristics. The prominent wide emission was centered at around 593 nm (2.09 eV). In the near-UV/blue region, weaker bands were detected at around 385 nm (3.2 eV) and 474 nm (2.6 eV). Also, low-intensity emissions were detected at around 704 nm (1.7 eV) and 786 nm (1.5 eV) within the near-infrared wavelength range.

3.6 Raman Spectroscopy

Raman spectroscopy (model XploRA PLU, HORIBA Scientific, Palaiseau, France) was employed to elucidate the vibrational fingerprint and structural ordering of the synthesized WO₃ nanoparticles. As shown in Fig. 6, the spectrum was acquired over a broad wavenumber range (0–4525 cm⁻¹), revealing multiple resolved bands. An intense band was observed at (~334 cm⁻¹). A prominent band was also observed at (~709 cm⁻¹). No distinct band was detected in the (~950–960 cm⁻¹) region.

3.7 FTIR Spectroscopy

The Fourier transform infrared (FTIR, Model IRAffinity-1, Shimadzu, Kyoto, Japan) spectrum of the produced tungsten oxide nanoparticles, derived from *Petroselinum crispum* leaf extract, is shown in Fig. 7. The spectrum of the WO₃ NPs shows two weak bands in the mid-infrared region at approximately 2159 and 2026 cm⁻¹. The most significant features of the FTIR spectrum are located in the fingerprint region 900–400 cm⁻¹. A specific band was observed at around 756 cm⁻¹. In addition, strong absorption bands were detected at around 602 and 555 cm⁻¹, while a band was also detected near 417 cm⁻¹. No intense peaks were observed in the higher wavenumber region (3000–3500 cm⁻¹).

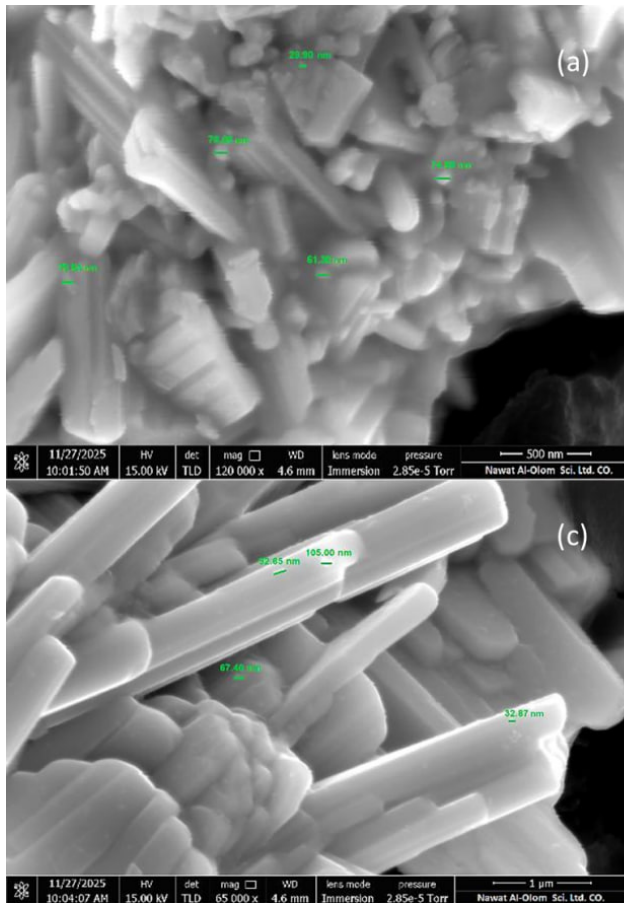


Fig. 2. Surface morphology of WO₃ nanoparticles. (a,c) field-emission scanning electron microscopy (FE–SEM) images of the green-synthesized rod-like WO₃ nanoparticles, and (b,d) their corresponding particle size distribution histograms determined from SEM images. Scale bar = 500 nm in (a); scale bar = 1 μm in (c). SEM, scanning electron microscopy.

3.8 AFM Surface Morphology

Atomic force microscopy (AFM) (AFM/SPM Du-alScope DS, Helmut Fischer GmbH, Sindelfingen, Germany) was utilized to examine the surface topography and statistical roughness parameters of the prepared sample. In Fig. 8 the AFM images obtained from scan regions of (4 × 4 μm²) and (10 × 10 μm²) exhibit a nanostructured surface marked by irregular height distributions and prominent protrusions. Fig. 9 shows quantitative analysis yielded an arithmetic mean height (Sa) of (20.40 nm) and a root mean square roughness (Sq) of (31.13 nm). The positive asymmetry value Ssk = 1.860 and the high kurtosis Sku = 11.55.

3.9 Gas Sensor Measurements

The response of the WO₃-based sensor to NO₂ and NH₃ was evaluated at different operating temperatures (room temperature, 100 °C, and 200 °C) with a constant gas concentration of 200 ppm. The response (S%) was determined using Eqn. 1 [18]:

$$S(\%) = \left| \frac{R_a - R_g}{R_g} \right| \times 100\% \quad (1)$$

Where R_a is the resistance of the sensor in dry air, R_g is the resistance in the presence of test gas.

3.9.1 Response to NO₂

The Table 2 presents the gas sensor values for NO₂ detection. The sensor exhibited a sensitivity of 45.41% at ambient temperature, which significantly increased to a maximum of 77.68% at 100 °C. However, increasing the temperature to 200 °C resulted in a sensitivity decrease to 38.29% as seen in Fig. 10. The response and recovery times varied from 17.37 to 24.12 seconds and 18 to 19.08 seconds, respectively. Exposure to NO₂ gas resulted in an increase in sensor resistance.

Table 2. Gas sensing parameters of WO₃ nanoparticles for 200 ppm NO₂.

Sample	Gas	T (°C)	S%	tres (s)	trec (s)	R change
WO ₃	NO ₂	RT	45.41	18.63	18.00	↑ Increase
		100	77.68	24.12	18.81	
		200	38.29	17.37	19.08	

RT, room temperature.

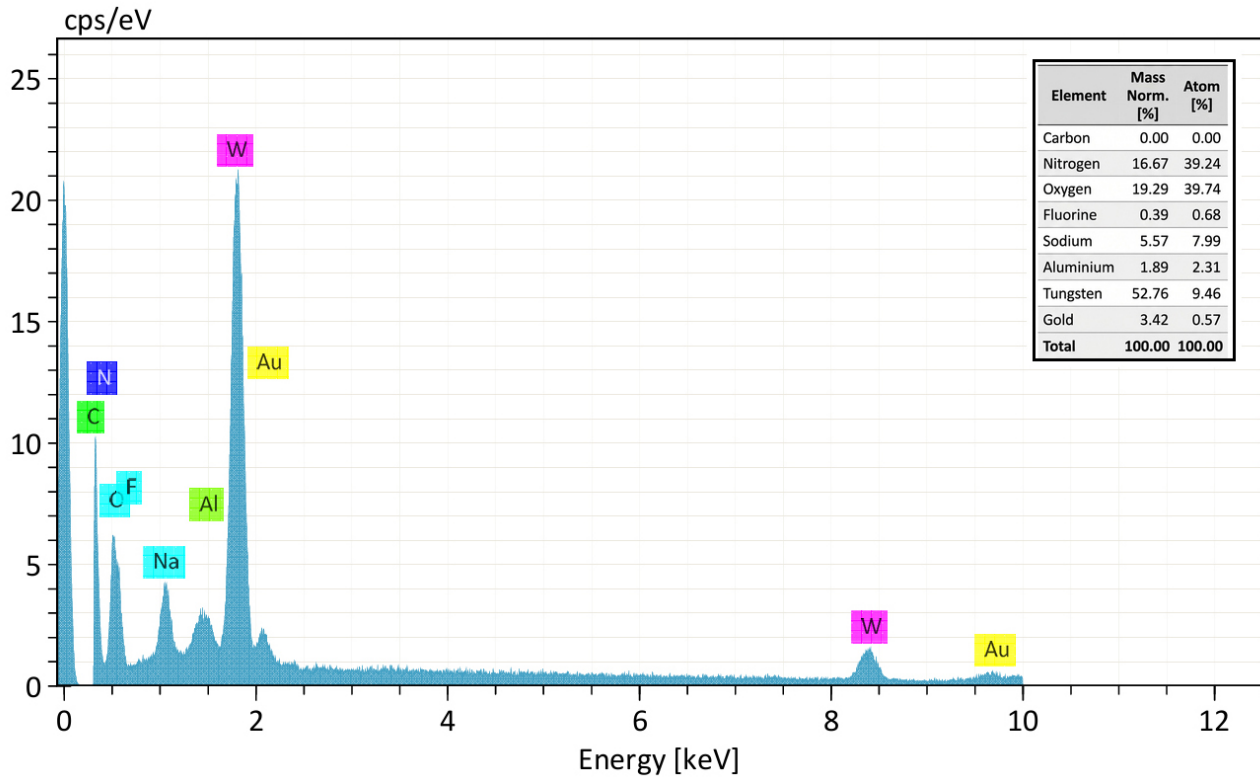


Fig. 3. The EDX Spectrum for WO₃ NPs. NPs, nanoparticles; EDX, energy-dispersive X-ray spectroscopy.

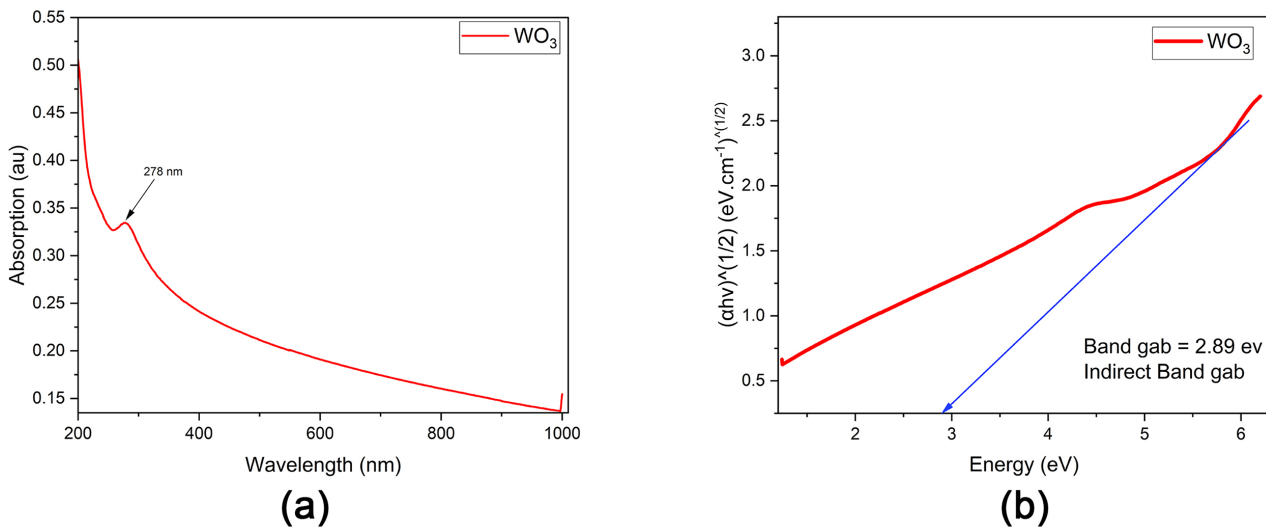


Fig. 4. Optical properties of the synthesized WO₃ nanoparticles. (a) UV-Vis spectrum and (b) Tauc plot of WO₃ optical bandgap.

3.9.2 Response to NH₃

In contrast, the sensor exhibited distinct temperature-dependent behaviour in response to NH₃ Table 3. The sensitivity diminished from 28.35% at room temperature to 21.81% at 100 °C, subsequently rising to a peak of 46.04% at 200 °C, shown in Fig. 11. The optimal response time of 13.23 s was recorded at this temperature. Upon exposure to NH₃, the sensor resistance diminished.

4. Discussion

4.1 Crystal Structure and Microstructural Analysis

The XRD results confirm the successful formation of a monoclinic crystalline structure, demonstrating the remarkable phase purity of the produced nanoparticles. The clarity and prominence of the diffraction peaks indicate the high crystallinity of the green-synthesized WO₃ nanoparticles, verifying the nanocrystalline characteristics of the synthesized sample.

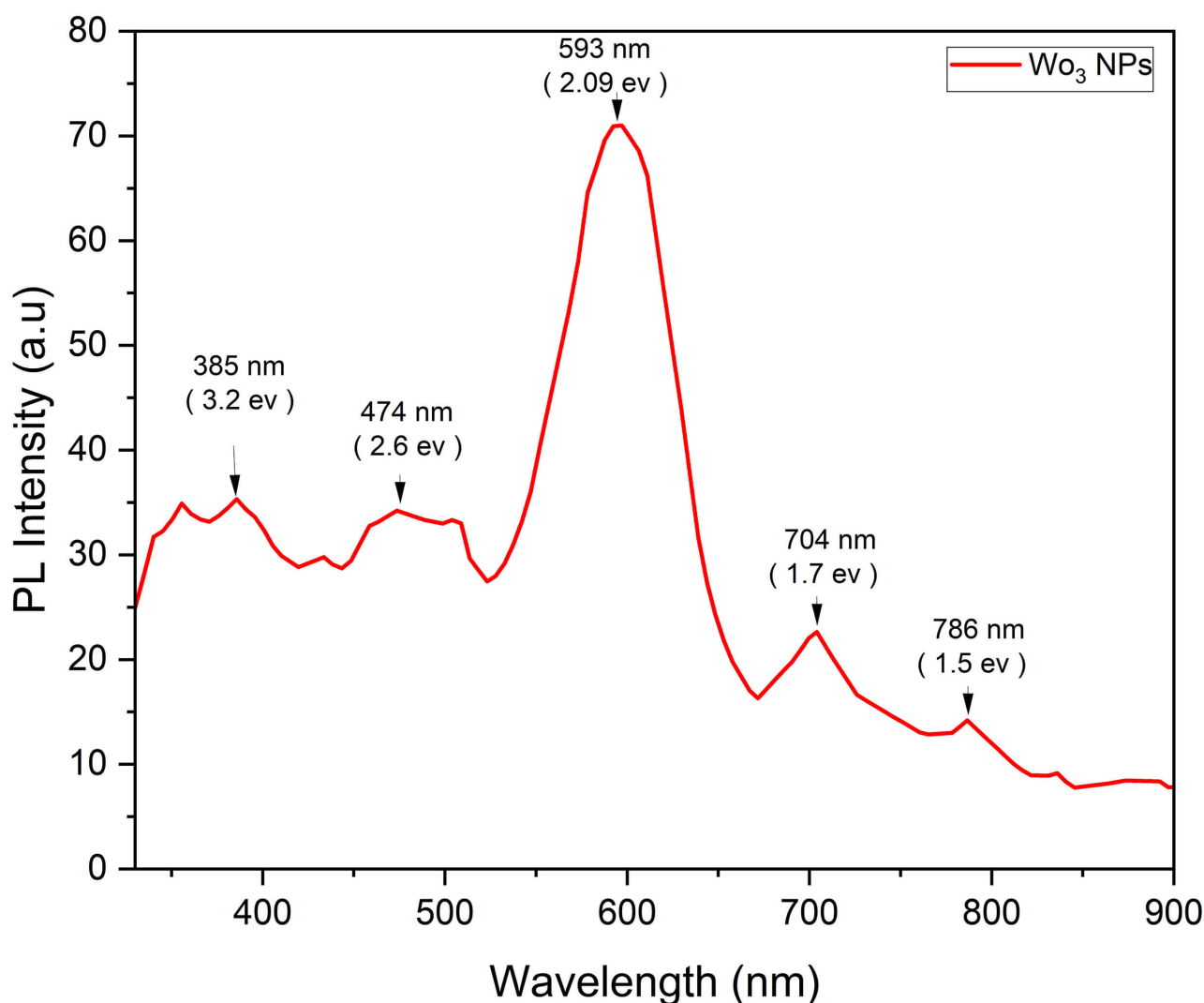


Fig. 5. Photoluminescence (PL) spectrum of WO_3 .

Table 3. Gas sensing parameters of WO_3 nanoparticles toward 200 ppm NH_3 .

Sample	Gas	T (°C)	S%	tres (s)	trec (s)	R change
WO_3	NH_3	RT	28.35	18.36	16.74	↓ Decrease
		100	21.81	17.01	19.53	
		200	46.04	13.23	15.48	

The determined average crystallite size (20.304 nm) was compared with values documented in the literature. The findings demonstrate strong concordance with Yadav et al. (2025) [19], who indicated a crystallite size of 20.6 nm, and Tijani et al. (2019) [20], who documented crystallite sizes between 5.90 and 27.14 nm. The result derived from the study is within the specified range.

The precisely estimated average dislocation density (3.695×10^{15} lines/ m^2), along with the corresponding mean micro-strain (1.979×10^{-3}) and stress (0.594 GPa), confirm the presence of structural defects induced by the green bio-reduction process. These microscopic imperfections are highly beneficial, as they provide abundant active sur-

face sites that significantly enhance the gas-sensing performance.

4.2 Surface Morphology and Particle Distribution

The rod-like morphology observed in the FE-SEM images is due to the elevated surface energy of the nanoparticles and the stabilizing influence of bioactive chemicals found in the plant extract during production. These observations are consistent with previous studies reporting rod-like morphologies for WO_3 nanoparticles prepared via green synthesis routes or other methods [16,21].

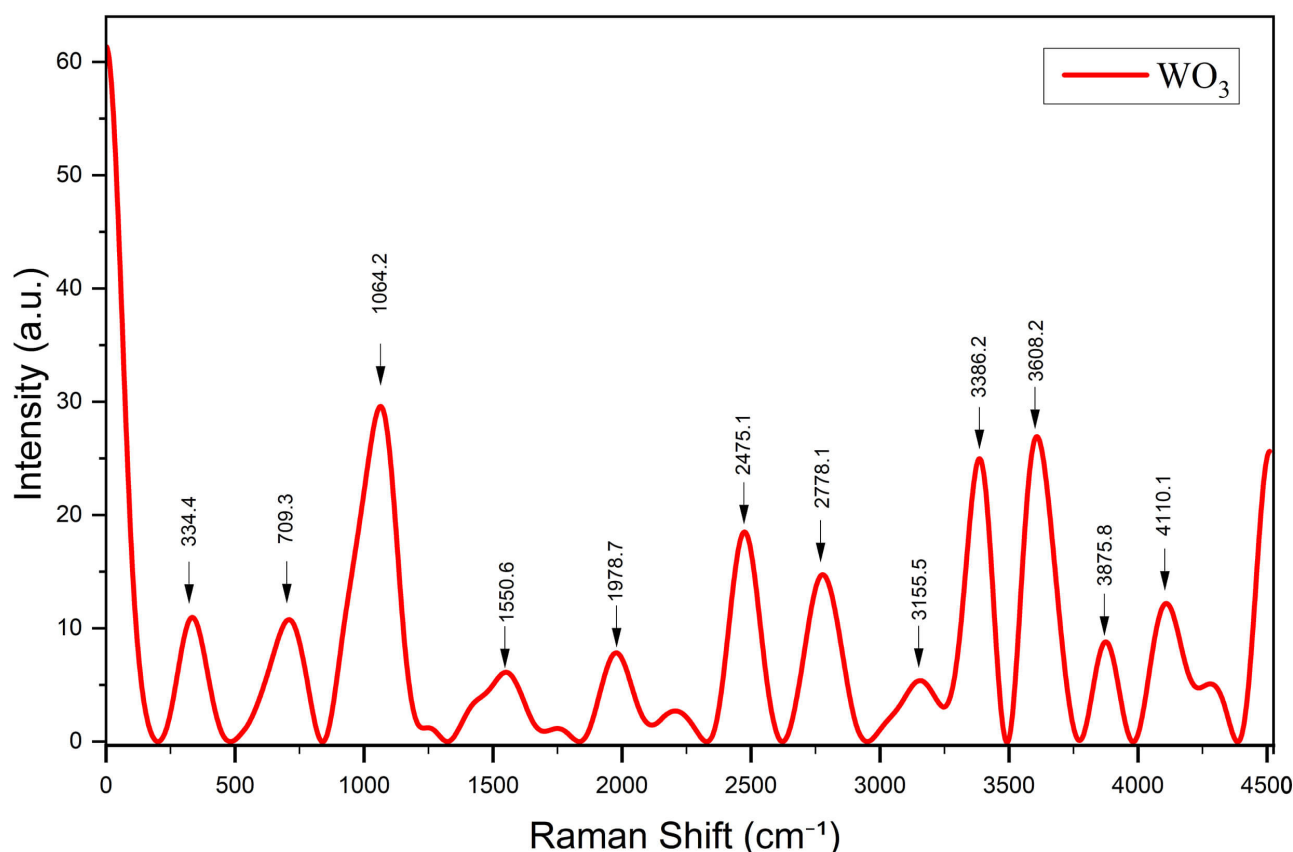


Fig. 6. Raman spectra of green-synthesized tungsten trioxide (WO_3) nanoparticles.

4.3 Elemental Composition and Purity

The EDX quantitative results, showing a tungsten content of 52.76 wt% and an oxygen content of 19.29 wt%, verify the effective synthesis of the tungsten oxide composition. The modest peaks associated with nitrogen and sodium are directly linked to leftover precursor species from sodium tungstate dihydrate and certain phytochemicals derived from the parsley extract utilized in the synthesis. Aluminum and fluorine residues presumably came from the sample substrate holder. The gold (Au) peak at around 2.2 keV was put there on purpose during the gold-sputtering process before the SEM-EDX examination. The EDX findings definitively validate the chemical purity of the produced WO_3 nanoparticles devoid of any unforeseen metallic contaminants.

4.4 Optical Properties

The distinct absorption peak at around (278 nm) [22], along with the progressive decline in absorbance within the visible spectrum, clearly reflects a protracted optical response intrinsically linked to the nanoscale characteristics of the synthesized material. The indirect band gap estimate of roughly (2.89 eV) was compared with previously reported values. Anggraini et al. [23] observed a band gap energy of roughly (2.9 eV) for plant-mediated WO_3 nanoparticles, whereas Ruby et al. [17] found a value of about (2.23

eV), and Fernández-Domene et al. [16] reported a band gap of (2.6 eV) for nanostructured WO_3 .

4.5 Photoluminescence Analysis

The multi-band emission characteristics of the PL spectrum are indicative of defect-related electronic states. The prominent wide emission centered at around 593 nm (2.09 eV) aligns with visible luminescence influenced by defect levels associated with oxygen vacancies inside the band gap, as well as surface or localized states frequently seen in nanostructured WO_3 [24,25]. In the near-UV/blue region, the weaker bands detected at around 385 nm (3.2 eV) and 474 nm (2.6 eV) align well with documented emissions linked to resonant/near-edge processes and band-band or shallow-defect-related transitions in WO_3 -based systems [24,26].

The low-intensity emissions detected at around 704 nm (1.7 eV) and 786 nm (1.5 eV) reside within the near-infrared wavelength range, which has been linked to deep defect-mediated mechanisms, including polaron relaxation and coupling-related states in sub-stoichiometric tungsten oxides [27]. The presence of band-band and defect-level transitions, especially those influenced by oxygen-vacancy states, indicates a defect-rich electronic structure for the produced WO_3 nanoparticles [24,27].

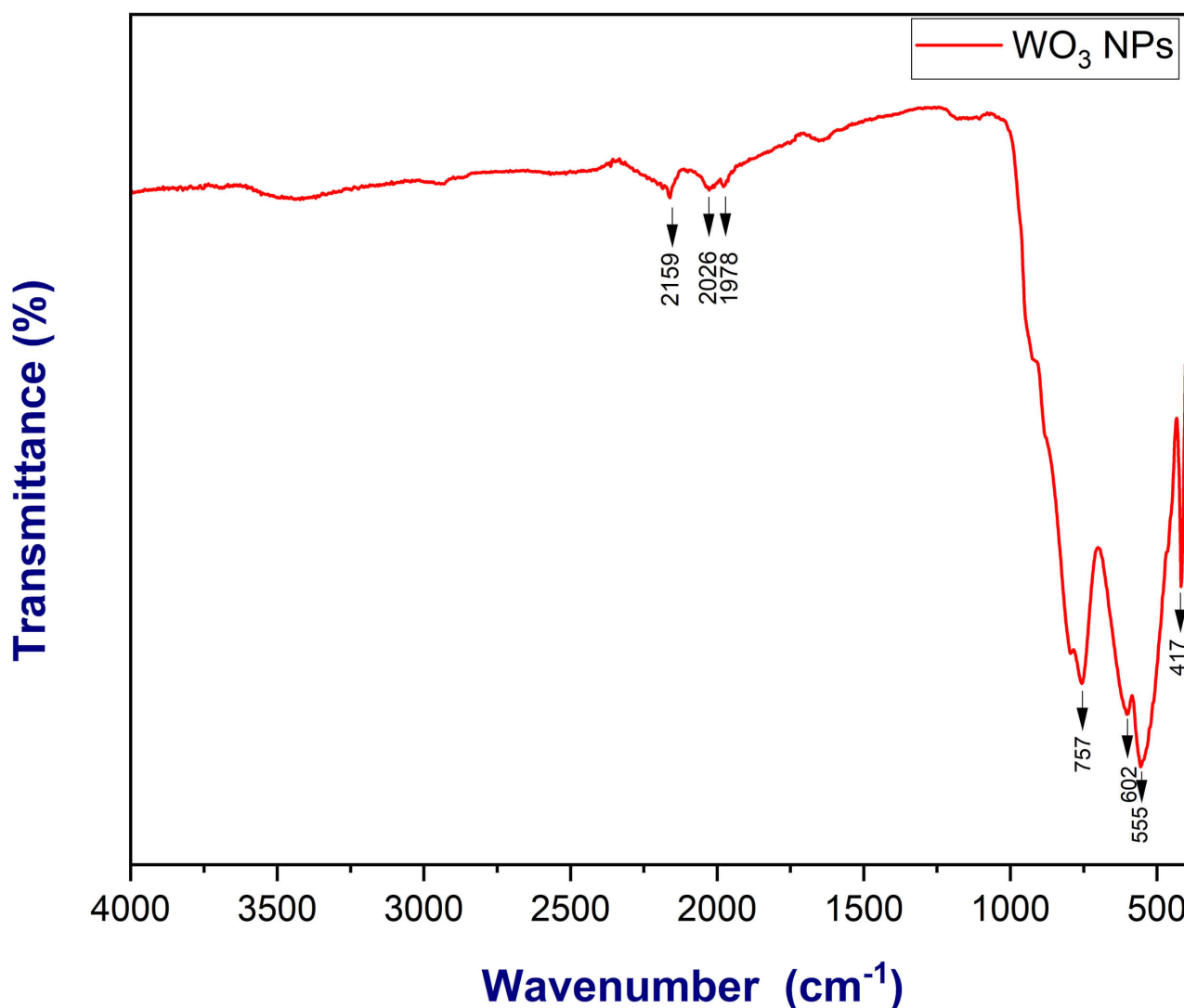


Fig. 7. FTIR Spectrum of WO_3 . FTIR, Fourier transform infrared.

4.6 Raman Vibrational Analysis

In accordance with reported WO_3 Raman assignments, the lattice/deformation contribution is typically observed in the $200\text{--}400\text{ cm}^{-1}$ region, while the stretching modes are mainly distributed between 600 and 900 cm^{-1} , with a possible terminal W=O contribution expected near 950 cm^{-1} . From this spectrum, the intense band at ($\sim 334\text{ cm}^{-1}$) falls within the deformation–lattice region, consistent with O–W–O bending/lattice deformation behavior of WO_3 [15].

A prominent band at ($\sim 709\text{ cm}^{-1}$) is assigned to framework (O–W–O / W–O–W) stretching vibrations in agreement with the characteristic monoclinic-mode window reported around $714\text{--}717\text{ cm}^{-1}$ and 805 cm^{-1} for WO_3 [15,28]. Hydrated $\text{WO}_3 \cdot x\text{H}_2\text{O}$ typically displays a prominent terminal W=O stretching band around 960 cm^{-1} , whereas dehydration or the formation of monoclinic WO_3 results in the disappearance of this terminal band and

the prominence of vibrational modes below 300 cm^{-1} and within the range of $900\text{--}600\text{ cm}^{-1}$ [29].

The lack of distinct ($\sim 950\text{--}960\text{ cm}^{-1}$) terminal feature along with the predominance of lattice and framework bands indicates that the product is primarily non-hydrated/crystalline WO_3 , aligning with the identification of the monoclinic phase [15,29]. A significant band at around 709 cm^{-1} is ascribed to the framework (O–W–O / W–O–W) stretching vibrations, aligning with the characteristic monoclinic-mode window seen at $714\text{--}717\text{ cm}^{-1}$ and 805 cm^{-1} for WO_3 [30]. The presence and configuration of the diagnostic lattice and stretching bands offer vibrational proof of the structural order in WO_3 nanoparticles.

4.7 FTIR Vibrational Analysis

The FTIR spectrum displays several characteristic vibrational bands that clarify the chemical bonding and inorganic structure of the produced WO_3 nanoparticles. The two weak bands in the mid-infrared region at approximately

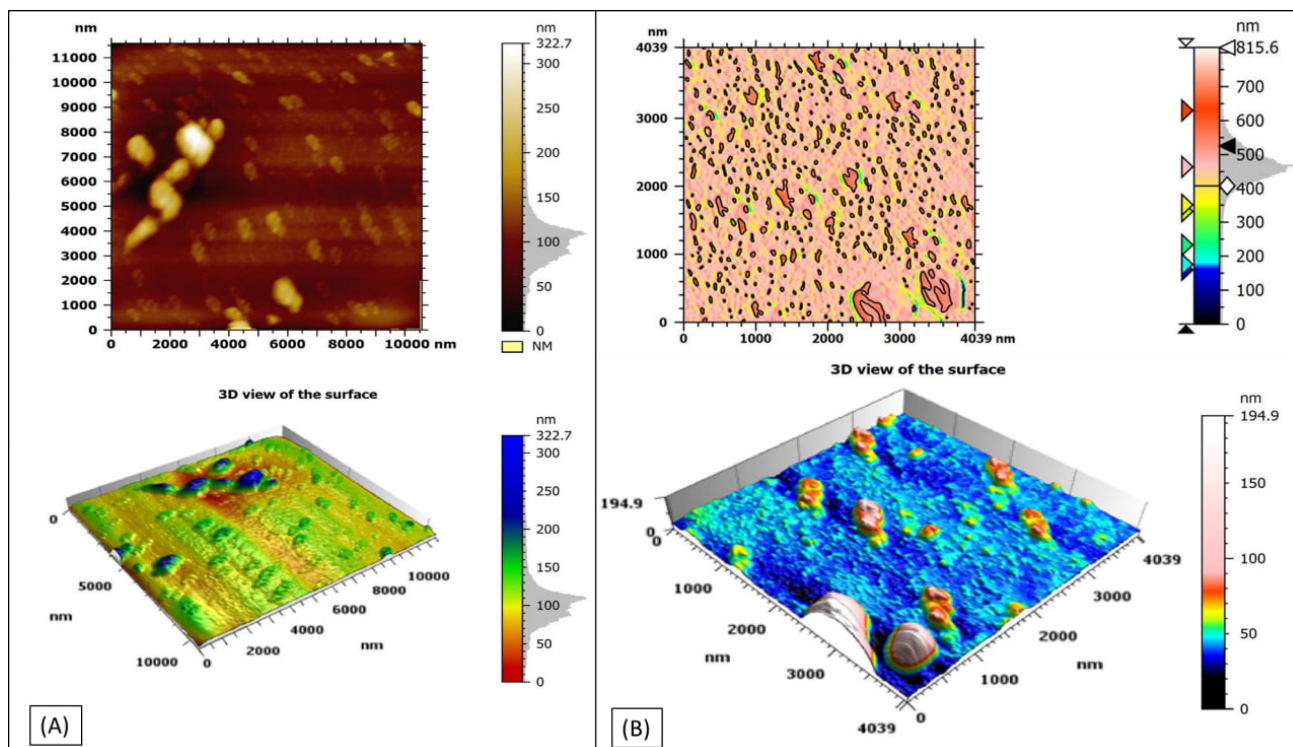


Fig. 8. AFM topographic analysis of the synthesized WO_3 nanoparticles. (A) AFM 2D and 3D topographic images of the WO_3 surface ($1 \times 1 \mu\text{m}^2$). (B) AFM 2D and 3D topographic images of the WO_3 surface ($4 \times 4 \mu\text{m}^2$). AFM, Atomic force microscopy.

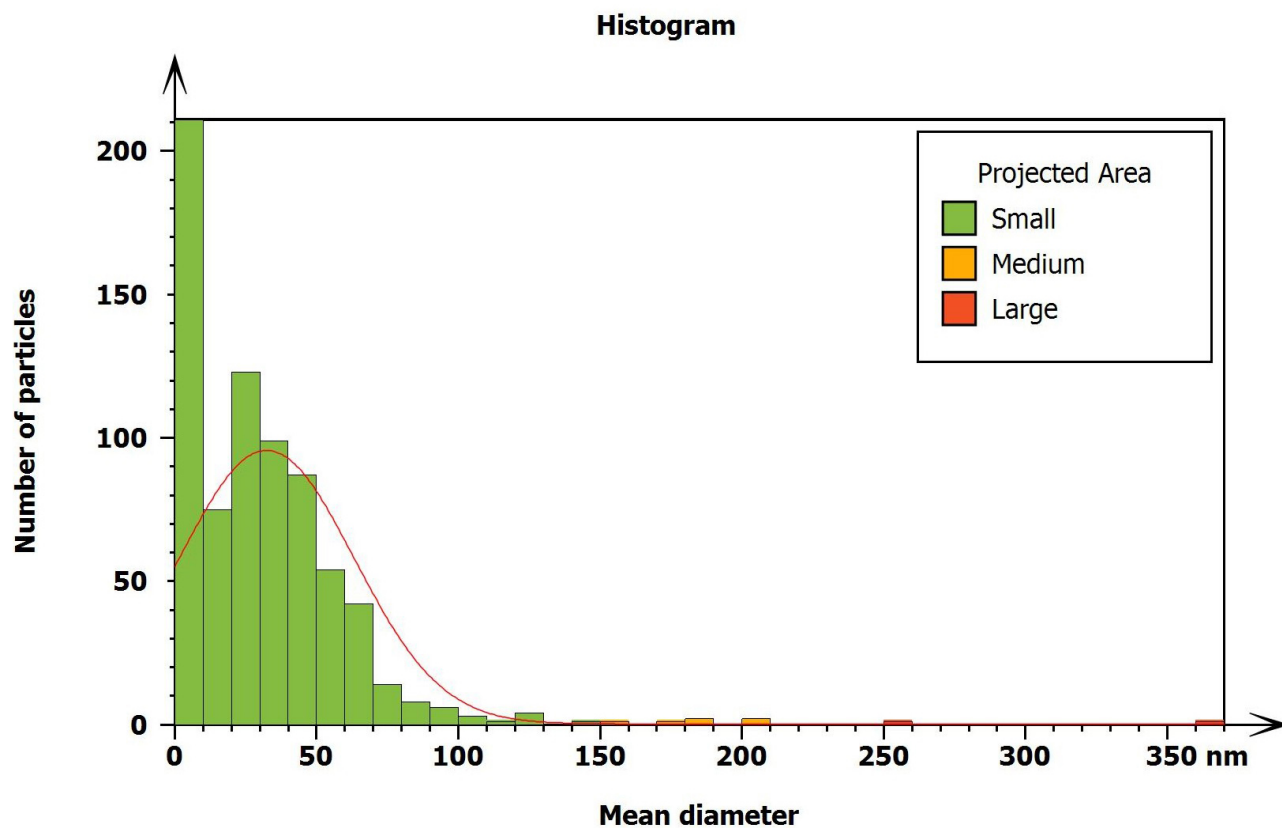


Fig. 9. Histogram of particle size distribution obtained from AFM data.

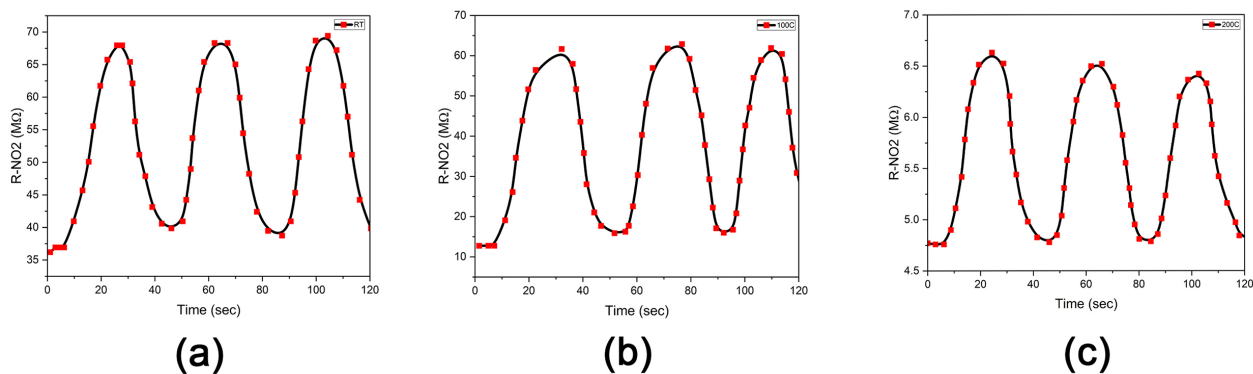


Fig. 10. Dynamic sensing response to NO₂ gas. Resistance–time response of the WO₃-based gas sensor to NO₂ at (a) room temperature, (b) 100 °C and (c) 200 °C.

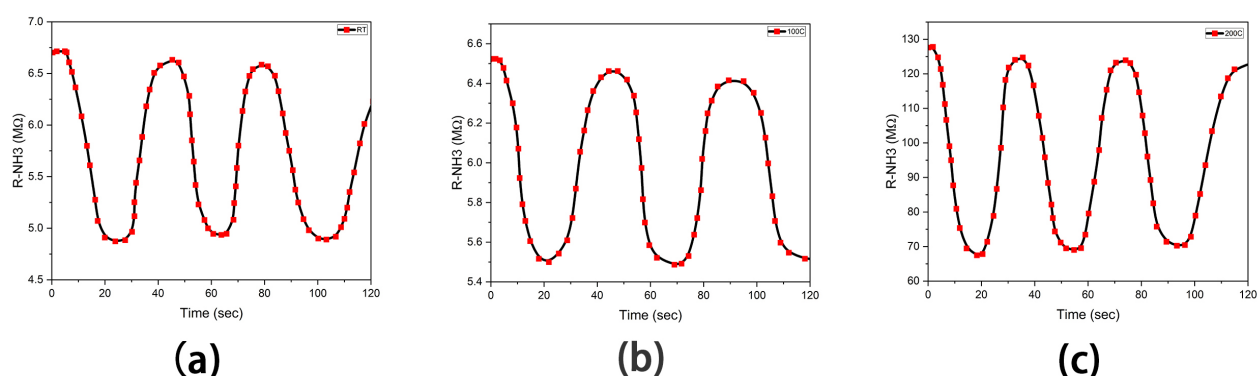


Fig. 11. Dynamic sensing response to NH₃ gas. Resistance–time response of the WO₃-based gas sensor to NH₃ at (a) room temperature, (b) 100 °C and (c) 200 °C.

2159 and 2026 cm^{-1} can be attributed to overtone or combination modes and residual organic species from the plant extract physisorbed on the nanoparticle surface, indicating the presence of a small amount of organic material originating from the plant extract. The most significant features of the FTIR spectrum are located in the fingerprint region, 900–400 cm^{-1} which is characteristic of tungsten oxide lattices [31].

The specific band seen at around 756 cm^{-1} is attributed to the stretching vibrations of (W–O–W) links inside the WO₃ crystal lattice. This peak confirms the existence of WO₆ octahedral units, which serve as the essential components of the monoclinic WO₃ structure [17]. The strong absorption bands at around 602 and 555 cm^{-1} correspond to the bending vibrations of O–W–O bonds, while the band detected near 417 cm^{-1} is related to additional lattice vibrational modes of W–O bonds.

These bands clearly show that tungsten–oxygen networks have formed and that WO₃ nanoparticles have been successfully made. The absence of intense peaks in the higher wavenumber region (3000–3500 cm^{-1}) suggests minimal hydroxyl groups and adsorbed water on the nanoparticle surface. The FTIR findings are in excellent agreement with the XRD results, which confirmed the crys-

talline structure of WO₃, demonstrating strong consistency between vibrational and crystallographic analyses [6].

4.8 Surface Topography Analysis

The AFM images affirm an uneven nanoscale morphology. The arithmetic mean height (S_a) of 20.40 nm and root mean square roughness (S_q) of 31.13 nm indicate moderate surface roughness. The positive asymmetry value $S_{sk} = 1.860$ suggests a surface dominated by elevated features rather than deep valleys, while the high kurtosis $S_{ku} = 11.55$ reflects sharp and well-defined summit structures. These attributes are frequently linked to a greater effective surface area and improved surface-driven features [32].

4.9 Gas Sensing Performance and Mechanism

4.9.1 Temperature-Dependent Sensing Behavior

The bell-shaped temperature dependency indicates that 100 °C is the best temperature for NO₂ detection [4]. The response and recovery times, varying from 17.37 to 24.12 seconds and 18 to 19.08 seconds respectively, indicate rapid sensor kinetics. The increase in sensor resistance upon exposure to NO₂ gas is indicative of n-type semiconductor behaviour in response to oxidizing gases [3].

Table 4. Comparison of the gas sensing performance of the present green-synthesized WO₃ nanoparticles with other reported WO₃-based materials.

Sensing Material	Synthesis Method	Target Gas (Conc.)	Opt. Temp. (°C)	Response	Ref.
WO ₃ NPs (Rod-like)	Green (Parsley extract)	NO ₂ (200 ppm)	100	77.68%	Present work
		NH ₃ (200 ppm)	200	46.04%	
WO ₃ nanoplates	Chemical (Solvothermal)	Formaldehyde (200 ppm)	350	(R _a /R _g) 16.5	Wu et al., [2025] [33]
WO ₃ nanopowder	Green (Vitamin C surfactant)	Acetone (10 ppm)	400	(ΔG/G ₀) 11	Pakdel et al., [2023] [15]
WO ₃ ·H ₂ O nanosheets	Sonochemical	NH ₃ (100 ppm)	RT	(R _{air} /R _{gas}) 13.4	Chang et al., [2011] [34]
WO ₃ nanoparticles	Surfactant-tailored (DFOM)	NO ₂ (1 ppm)	200	(S) >500	Pokhrel et al., [2009] [3]

For NH₃ detection, the sensitivity pattern designates 200 °C as the optimal operating temperature [4]. Upon exposure to NH₃, the sensor resistance diminished due to electron donation, aligning with n-type characteristics in response to reducing gases.

4.9.2 Gas Sensing Mechanism

The gas sensing mechanism of n-type WO₃ nanoparticles is fundamentally dictated by the surface-controlled depletion concept. In ambient air, oxygen molecules adsorb onto the WO₃ surface, seizing electrons from the conduction band to generate chemisorbed oxygen species (O₂⁻, O⁻, or O²⁻) thereby forming an electron depletion layer (EDL) and resulting in elevated baseline resistance [4,33]. Upon exposure to an oxidizing gas such as NO₂, the gas molecules acquire more electrons hence expanding the (EDL) and augmenting the resistance. In contrast, the introduction of a reducing gas like NH₃ leads to a reaction with the pre-adsorbed oxygen species, releasing the trapped electrons into the conduction band this diminishes the EDL and thus reduces the total sensor resistance [4].

The change in inverse resistance shows that the green-synthesized WO₃ nanoparticles are n-type semiconductors. NO₂ is most sensitive at 100 °C (77.68%), and NH₃ is most sensitive at 200 °C (46.04%) [4]. The green synthesis employing parsley extract provides controlled morphology enhanced surface properties, dual-gas sensing capabilities, and environmental sustainability by removing harmful compounds, making it suitable for practical gas sensing applications [15].

4.9.3 Comparative Performance Analysis

To assess the efficacy of the green-synthesized WO₃ nanoparticles their gas-sensing properties were compared with those of previously documented WO₃-based sensors (Table 4, Ref. [3,15,33,34]). In summary, the parsley-mediated WO₃ nanoparticles exhibit competitive dual-gas sensitivity at moderate temperatures (100–200 °C) and rapid response/recovery kinetics (13–24 seconds) in contrast to other nanostructures that necessitate elevated operating temperatures (350–400 °C) or intricate chemical processes. This underscores their efficacy as practical and environmentally sustainable options for gas monitoring.

4.10 Limitations

Despite the promising results obtained in this study, several limitations should be acknowledged. The gas sensing measurements were conducted at a single gas concentration of 200 ppm for both NO₂ and NH₃; therefore, the sensor response across a wider concentration range remains unexplored. Additionally, only three operating temperatures (room temperature, 100 °C, and 200 °C) were evaluated, which may not fully capture the complete temperature-dependent behavior of the sensor. The long-term stability and repeatability of the WO₃-based sensor under prolonged or cyclic gas exposure conditions were not investigated in the present work. Furthermore, the selectivity of the sensor toward NO₂ and NH₃ in the presence of other interfering gases was not examined. Future studies should address these aspects to further validate the practical applicability of the green-synthesized WO₃ nanoparticles in real-world gas monitoring environments.

5. Conclusion

Tungsten oxide nanoparticles (WO₃ NPs) have been successfully synthesized in an environmentally benign approach using *Petroselinum crispum* (parsley) leaf extract as a natural reducing and capping agent in the chemical reaction. The crystal structure validated by XRD confirmed the monoclinic structure of tungsten oxide, and the FE-SEM results revealed a rod-like morphology of the tungsten oxide nanoparticles, demonstrating a homogeneous arrangement.

This green synthesis method, which yields tungsten oxide nanoparticles with a distinct shape and enhanced surface properties, is considered a natural, renewable, low-cost, and effective bio-route for the synthesis of high-purity tungsten oxide nanostructures. It is then used in critical applications such as gas sensors for detecting NO₂ and NH₃, operating efficiently at optimal temperatures of 100 °C and 200 °C, respectively.

Availability of Data and Materials

All data generated or analyzed during this study are available from the corresponding author on reasonable request.

Author Contributions

The research study was designed by HAATA. MSI carried out the experiments and analyzed the data. Both authors contributed to editorial changes in the manuscript. Both authors read and approved the final manuscript. Both authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Fresh *Petroselinum crispum* (parsley) leaves used in this study were obtained from a local market in Wasit, Iraq.

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Conflicts of Interest

The authors declare no conflicts of interest.

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