

Structural, Dielectric, Optical, and Electrochemical Insights into Enhanced OER Activity of $\text{Y}_3\text{Fe}_5\text{O}_{12}$ over YFeO_3 Ferrite Nanoparticles for Hydroelectric Cell Applications

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Abstract

YFeO_3 (YF) and $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YGF) nanoparticles were synthesized by a modified low-temperature sol-gel auto-combustion route to elucidate structure–property relationships governing oxygen evolution reaction (OER) and hydroelectric cell (HEC) performance. Rietveld-refined XRD confirmed orthorhombic YF and cubic garnet YGF phases, while Raman and HRTEM established phase purity, crystallinity, and morphology. YGF exhibited higher dielectric permittivity (23.20), lower dielectric loss (0.765), larger specific surface area ($12.815 \text{ m}^2\text{g}^{-1}$), and oxygen-vacancy-rich surface chemistry, facilitating electrochemical charge transfer. Accordingly, YGF showed higher ECSA (18.25 cm^2), C_{dl} (0.73 mF cm^{-2}), and lower R_{ct} (359Ω) than YF. YGF delivered superior OER activity with an overpotential of 392 mV at 10 mA cm^{-2} and a Tafel slope of 133 mV dec^{-1} . The YGF-based HEC achieved 14.123 mA short-circuit current, 0.981 V open-circuit voltage, and 13.854 mW maximum power, demonstrating its potential for sustainable hydroelectric energy conversion. These findings establish YGF as a promising multifunctional energy-conversion material.

Keywords: Garnet Ferrites, Green Energy, Hydroelectric cells, Electrocatalyst, Oxygen evolution reaction.

1. Introduction

Degradation of environment and scarcity of energy due to the over-burning of fossil fuels aiming towards sustainable energy progresses which have now become a major concern these days. Till date, various methods such as CO_2 reduction [1], Oxidation of methanol [2,3], Rechargeable metal-air batteries [4], and electrolysis of water [5], have been developed in order to convert and store green energies. Among all, OER has been considered as an essential and most feasible way enabling clean energy solutions, reducing dependency on fossil fuels, and improving the efficiency of O_2 production [6]. There is a need to develop those OER catalysts which reduce the overall energy input and making O_2 more viable. The recent research has

been directed toward developing cost-effective and earth-abundant materials to replace noble metals which are highly expensive. Among these, perovskite oxides with an ABO_3 -type structure have gained significant attention as promising electrocatalysts. Due to their remarkable adaptability and structural flexibility, perovskites can modify their electronic band structure and bond strength, thereby enhancing their catalytic efficiency [7,8]. Consequently, there is an equivalent thrust to develop the self-sustained and eco-friendly systems capable of producing electricity, one such device commonly known as hydroelectric cell (HEC). The device which has been a source of producing current only with the usage of water, not without any electrolyte or any external voltage [ref].

Owing to the large surface area and good catalytic efficiency of yttrium ferrites, they can be exploited to transform into HEC. These cells are believed to be the future source for the production of green energy or the generation of green energy using few droplets of water with the help of hydroelectric cells has been believed to be the source of clean, efficient, and cost-effective technique. Here, the perovskites have been utilized to develop these HEC as they contain a large number of unsaturated metal cations and surface hydroxyl groups which can strongly interact with water molecules and can promote the water adsorption and its dissociation because the large surface area HEC will attribute towards large value of current [9-11]. Rare earth orthoferrite perovskites with general formula of $MFeO_3$, where M is denoted for rare-earth metal, dwell under the category of multiferroic material, having disordered structure with orthorhombic crystal structure symmetry. Moreover, $YFeO_3$ or yttrium orthoferrite is a well-known multiferroic material with zero ferroelectric effect at room temperature due to its $Pnma$ space group [12]. Especially in the case of orthorhombic crystal structure, the Fe^{3+} ions are canted in the orthorhombic structure of $YFeO_3$ which would lead towards weak ferromagnetic behaviour. In the reported literature, a plethora of work on the structural, dielectric, and magnetic properties have been earlier done, but the efficacy of these ferrites on oxygen evolution reaction mechanism along with the HEC studies have not been studied yet. Whereas, Yttrium garnet ferrite (YGF) also comes under the category of ferrites exhibiting excellent magnetic as well as magneto-electric properties and it molds usability of yttrium ferrite in high frequency device applications [13]. YGF generally expressed by the chemical formula given as, $A_3B_5O_{12}$ where A is occupied by Y ions, B is represented by Fe ions. Mainly, there are 3 sub-lattices present in the YFG crystal system, (a) the dodecahedra, this is the site occupied by 3 yttrium (Y^{3+}) ions, (b) octahedral, site which is occupied by 2 iron (Fe^{3+}) ions and (c) Tetrahedral sites, this is the site occupied by three Fe^{3+} ions [14]. In the

structure of yttrium garnet ferrites, the 24 Fe^{3+} placed at octahedral sites, 16 Fe^{3+} ions occupy the tetrahedral sites, whereas remaining 24 RE^{3+} or Y^{3+} ions occupy the dodecahedral lattice positions in the lattice, and oxygen ions are distributed at the interstitial sites of lattice [15]. The A and B sites are occupied by both trivalent metal ions, which makes this crystal system exceptional and unique. YGF material is found to be useful in many applications such as microwave device applications including phase shifters devices, isolators, and circulators, etc [16]. Hence, it shows excellent magnetic properties as compared to other lattice systems. The garnet structure generally contains majorly 3 sub-lattices, the dodecahedra site or c-site is mainly occupied by the 3 Y^{3+} ions, whereas the octahedra or a-site is captured by the 2 Fe^{3+} ions, and the tetrahedral or d-site is engulfed by the 3 Fe^{3+} ions. Garnet ferrites are usually preferred as a suitable candidate for performing magnetic studies due to the co-existence of two trivalent metallic ions (Y^{3+} and Fe^{3+}) in the lattice sites. The most important interaction in the crystal system is the interaction between the iron atoms present at a and d sites, aligned in anti-parallel direction. During this process, the magnetic moment of two iron ions of d site will be cancelled by the magnetic moments of two Fe^{3+} ions present at a site. Hence, the net magnetic moment of the garnet ferrite is a result of the extra iron ions dwell at the d sites [17]. The control of homogeneity and composition of ions in the garnet ferrite is an essential parameter to decide their magnetic properties. Yttrium ferrite is considered as one of the best ferrites due to its high electric resistivity, low power losses, high radiation stability, moderate magnetic saturation values, etc [18]. Garnet ferrites dwell under the category of ferrimagnetic materials covering promising results in developing high-frequency devices. It is a versatile ceramic material with technological application in devices such as phase shifters, high quality filters, circulators, and many other electronic devices operating on high frequencies. These versatile applications exhibited by yttrium garnet ferrites are due to its extremely good properties such as high curie temperature, extremely high thermal stability, better chemical stability and thermal conductivity. Table 1 summarizes the comparative studies on overpotential, Tafel slopes, of the prepared samples with the other transition metal-based ferrites samples. Fig 1. represents the superior OER performance of $\text{Y}_3\text{Fe}_5\text{O}_{12}$ arises from the synergistic interplay between dielectric polarization, oxygen vacancies, and $\text{Fe}^{3+}/\text{Fe}^{2+}$ redox activity. The enhanced dielectric constant promotes efficient charge separation and transport by generating internal polarization fields. Simultaneously, oxygen vacancies act as active sites for OH^- adsorption and facilitate intermediate formation. The current work shows that how the surface mediated defects, porosity, lattice structure, cation distribution, optical bandgap, dielectric, magnetic properties affecting the overall material's performance as an efficient

catalyst in OER as well as for hydroelectric cell device application. In this way, the conducted study offered a new path relating dielectric studies with the oxygen evolution reaction (OER) mechanisms.

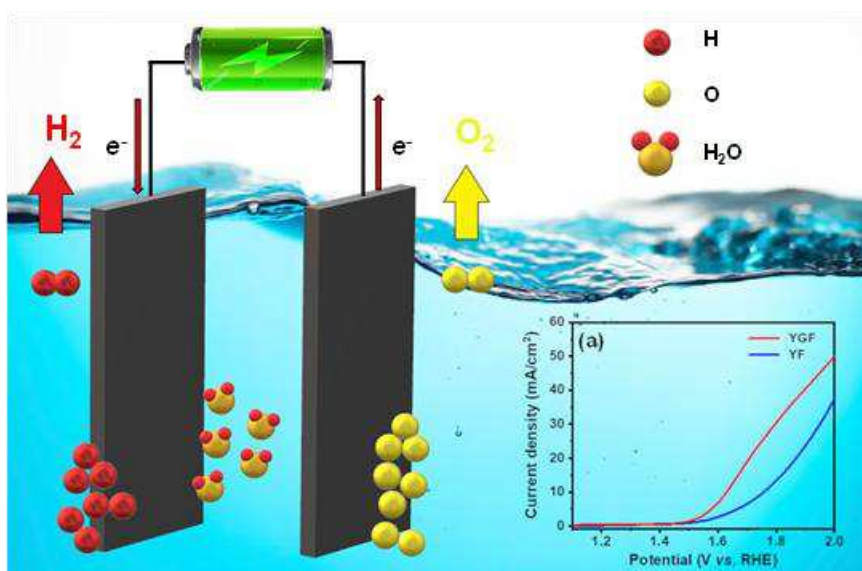


Fig 1. Schematic illustration of the enhanced oxygen evolution reaction (OER) mechanism over YGF catalyst.

Table 1. Comparison studies of prepared samples with the already reported works based on the transition metal based OER catalysts

Material	Overpotential/mV	Tafel slope/mVdec ⁻¹	ECSA/cm ²	References
NiFe ₂ O ₄ (T = 300°C)	464	103	1.28	[19]
NiFe ₂ O ₄ (T = 500°C)	539	125	0.62	[19]

CoFe ₂ O ₄ composite	370	283	35	[20]
CoFe ₂ O ₄ (powders)	435	126.3	-	[21]
CoFe ₂ O ₄ (hollow nanofibers)	414	95	107	[22]
NiFe ₂ O ₄ (fibers)	433	134	38	[22]
CoFe ₂ O ₄ (thin films)	490	54.2	1.75	[23]
YGF (Y ₃ Fe ₅ O ₁₂)	392	133	18.25	[present work]

2. Experimental Procedure

2.1. Precursors Required

All the precursors were utilized in nitrates form to prepare the nano-ferrites using sol-gel auto combustion method. Yttrium nitrate hexahydrate [Y(NO₃)₃.6H₂O, 99.6% purity, Sigma Aldrich], iron nitrate nonahydrate [Fe(NO₃)₃.9H₂O, 98% purity, CDH]. 5% Nafion[®] 117 solution (Sigma-Aldrich). DI water from Qualigens Ltd., Citric acid (C₆H₈O₇, Loba Chemie). Double distilled water (DDW), and ethanol were employed as solvents.

2.2. Synthesis of $YFeO_3$ (YF) and $Y_3Fe_5O_{12}$ (YGF) nanoparticles

Yttrium ferrite ($YFeO_3$) and yttrium garnet ferrite ($Y_3Fe_5O_{12}$) nanoparticles were prepared by using the sol-gel auto-combustion method (Fig 2). The required amounts of $Y(NO_3)_3 \cdot 6H_2O$ and $Fe(NO_3)_3 \cdot 9H_2O$ were separately dissolved in deionized water to prepare clear solutions. Each solution was stirred using a magnetic stirrer for 30 minutes to ensure uniform mixing. The yttrium nitrate solution was added to the ferric nitrate solution under constant stirring. Citric acid was used as a fuel and capping agent. The ratio of metal nitrates to citric acid was kept at 1:2. The pH of the resulting solution was maintained at around 7 by adding ammonia solution (NH_3). The mixture was heated and stirred continuously to $80^\circ C$ to form a viscous gel. The gel auto-ignited upon heating at $120^\circ C$, yielding a dark-coloured dry powder. The powder was ground to fine powder using a mortar and pestle and then sintered in a furnace at $900^\circ C$ for 4 h to enhance its crystallinity. The reground sintered material was cooled and ready for characterization and application.

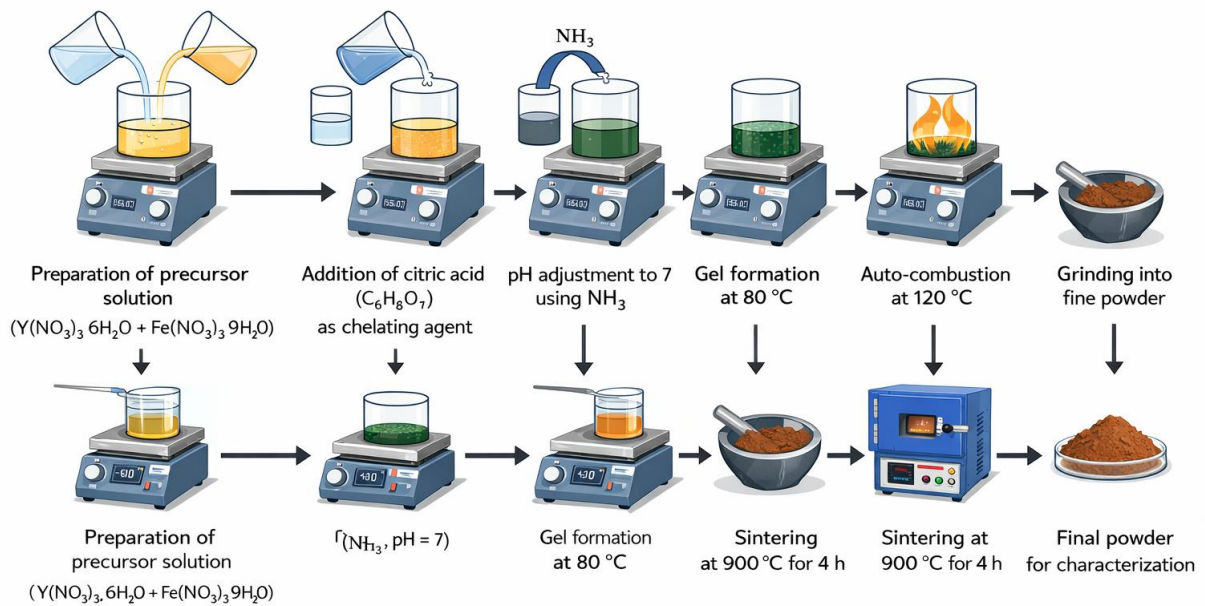


Fig 2. Stepwise synthesis of yttrium ferrite and yttrium garnet ferrite nanoparticles using sol-gel auto combustion synthesis route.

2.3. Electrochemical Studies

Electrochemical measurements were performed using a Metrohm Autolab Multichannel-204 potentiostat/galvanostat controlled by NOVA 2.1.4 software in a conventional three-electrode configuration. The catalyst-coated carbon electrode served as the working electrode, while a platinum (Pt) wire was employed as the counter electrode. A Hg/HgO electrode was used as the reference electrode throughout the oxygen evolution reaction (OER) studies. All electrochemical experiments were conducted in 1.0 M KOH electrolyte (pH = 13.8) prepared with double-distilled water. Linear sweep voltammetry (LSV) measurements for OER evaluation were recorded at a scan rate of 10 mV s⁻¹. Cyclic voltammetry (CV) measurements were carried out within the potential window of 0.1–0.2 V vs. Hg/HgO at scan rates ranging from 20 to 120 mV s⁻¹. Electrochemical impedance spectroscopy (EIS) analyses were performed over a frequency range of 100 kHz to 0.1 Hz at an overpotential of 392 mV. For consistency and comparison, all measured potentials were converted to the reversible hydrogen electrode (RHE) scale using the Nernst equation given below for OER activity evaluation [42]:

$$E_{(RHE)} = E_{(Hg/HgO)} + 0.059pH + E_{Ref} \quad (1)$$

2.4. Characterizations Techniques

All the measurements including structural, optical, electrical, vibrational, magnetic, impedance, and electrochemical studies have been performed using high resolution-based instruments. The structural measurements have been carried out using X-ray diffractometer [Xpert diffractometer with Cu-K α radiations of $\lambda = 1.5415$ Å with 2θ range extending from 10° to 80° at scan rate of 2°/min], Fourier-transform infrared spectroscopy (FTIR) which has been done using FTIR-spectrum 2 analyser (Perkin Elmer) in KBr mode. To analyse the surface states, X-ray photoelectron spectroscopy (XPS) was conducted using an Axis Supra photoelectron spectrometer (Maker: Kratos Analytical; Model: AXIS Supra). The morphological studies for the prepared samples have been done using Field emission scanning electron microscope of Zeiss Gemini SEM 500 Thermal field emission type with accelerating voltage extending from 0.02 V to 30 KV. The HRTEM results for the prepared samples have been obtained using Cryo high resolution transmission electron microscope, JEOL, NEOARM 200F. The optical studies including DRS and PL spectroscopy have been successfully carried

out using Agilent carry 5000 instrument and PL spectrum measurement system of Horiba, Fluorolog model FL 3-11. Vibrational studies for both samples have been obtained using Renishaw inVia confocal Raman spectrometer under the excitation wavelength of 532 nm. Electrical and impedance measurements for the samples have been measured using Novacontrol Technology impedance analyzer. Magnetic measurements have been recorded using Microsense (ADE-EV9) Vibrating Sample Magnetometer (VSM). The measurements related to surface area and pore radii calculation have been obtained using Quantachrome AUTOSORB iQ Brunauer-Emmett-Teller (BET) surface area analyzer. The X-ray photoelectron spectroscopy (XPS) results have been obtained using Kratos analytical Ltd (AXIS Supra) with monochromatic X-ray source of Al K α with energy 1486.6 eV.

3. Results and Discussion

3.1. Structural Studies

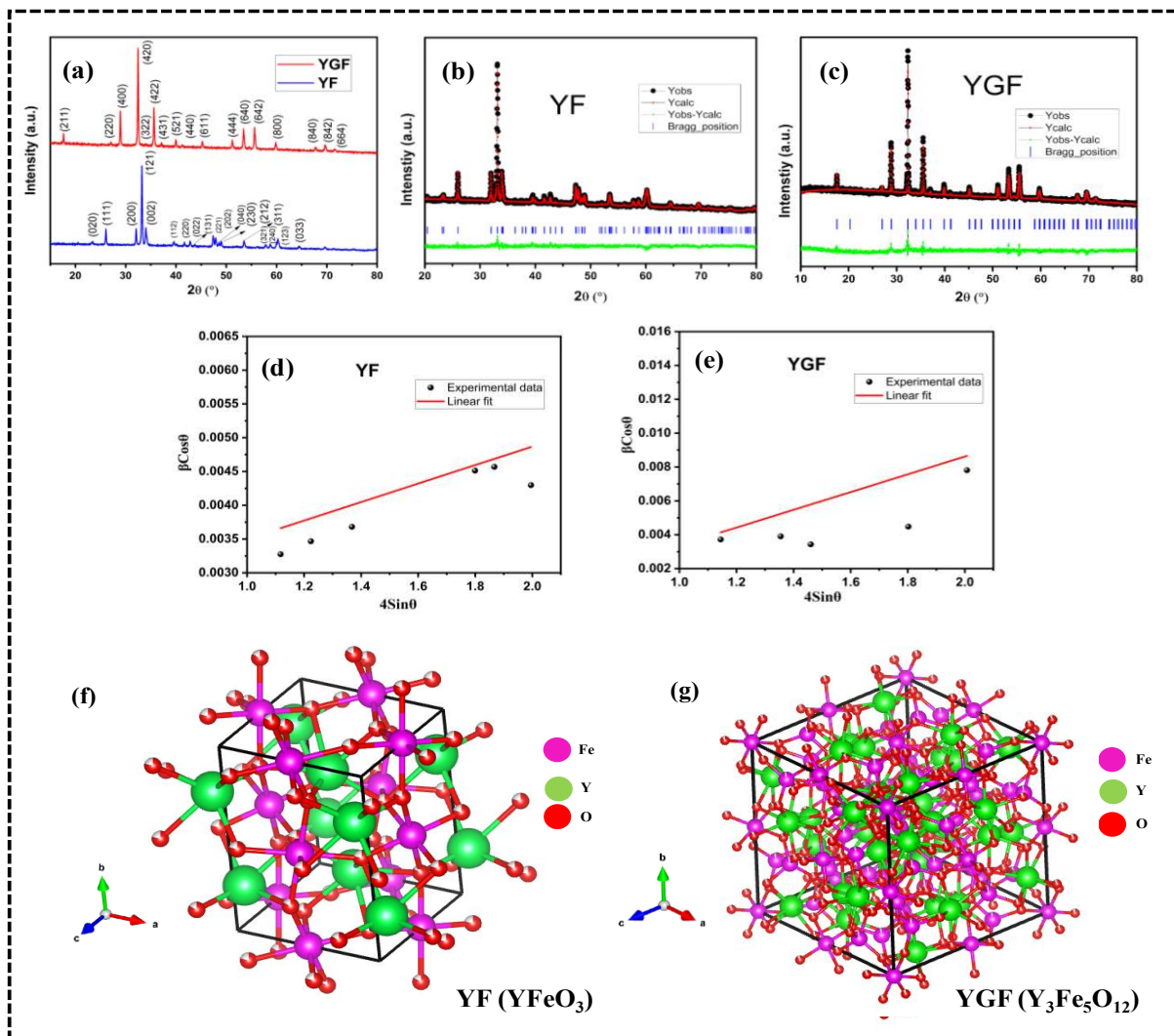


Fig 3. (a) XRD micrographs of pure yttrium ferrite (YF) and yttrium garnet ferrite (YGF), (b-c) Rietveld refined patterns of YF and YGF, (d-e) Williamson-Hall plots of pure YF and YGF, (f-g) Crystal structures of the prepared compositions obtained using VESTA software.

Fig 3 (a) exhibits the XRD pattern of the yttrium orthoferrite (YF) and yttrium garnet ferrite (YGF) scanned under a 2θ range varying from 20° to 80° with a scan rate of $1^\circ/\text{min}$. The reflection peaks obtained in the XRD pattern for the sample YF have been correctly matched with the JPCPS card number (ICSD #80865) and crystallizes in the space group of Pnma [24]. The absence of secondary peaks in both samples (YF and YGF) have further confirmed the formation of single-phase yttrium ferrites prepared using sol-gel method. The existence of most prominent peak in the XRD pattern of YF corresponds to $2\theta = 33.18^\circ$ and form as a result of the convolution of the three other reflection planes such as (200), (121), and (002) agrees with the reported literature [25]. The diffraction peaks obtained for YGF crystal structure has been well matched with the JCPDS card number #88502 which crystallized in Ia3d space group [26]. The sharp peaks can be observed in the XRD pattern of YGF sample even when it was sintered at 900°C for 4 h which suggests that sharp and highly nanocrystalline garnet ferrite nanoparticles can be formed even at $T < 1150^\circ\text{C}$ (Fig 3 (a)).

Fig 3 (b,c) shows the Rietveld refined XRD patterns of pure YF and YGF samples, obtained using FULLPROF suite software. From the Rietveld refinement, it has been observed that the experimental and the observed data are found to be in close agreement with each other for both samples. The refinement of the peak shape is obtained by selecting Pseudo Voight Thompson Cox hastings function which is mainly a linear combination of Lorentzian and Gaussian functions [27]. The refinement process began with adjusting global parameters, including background and scale factors. This was followed by refining LC, crystal orientation, asymmetries, metal ion occupancies, atomic coordinates, and isothermal parameters. Various parameters associated with the refinement such as residual factor (R_p), Weighted residual factor (R_{wp}), and goodness of fit (χ^2), along with structural parameters, density, volume of lattice, etc have been tabulated in Table 2. During the Rietveld analysis of pure YF, the Y^{3+} ions are assumed to occupy 4c lattice sites with atomic positions at $(0.5+\delta x, 0.25, \delta z)$, the Fe^{3+} ions accommodated at 4b lattice sites with atoms being positioned at $(0, 0, 0.5)$, and O^{2-} ions occupy the 4c lattice sites at position $(\delta x, 0.25, 0.5+\delta z)$. However, during the refinement of YGF, the yttrium ions occupy dodecahedral or c-sites, Fe^{3+} ions are equally distributed between

octahedral (a-sites) and tetrahedral sites (d-sites). Oxygen (O^{2-}) ions create a structural network that links and stabilizes the cations while preserving charge balance [28].

Williamson-Hall (W-H) plots are done to calculate the values of average crystallite size and the lattice strain induced in both samples. The W-H plot equation is mainly given as below (equation 2) as follows: [29]

$$\beta \cos \theta = \frac{k\lambda}{D} + 4\epsilon \sin \theta \quad (2)$$

where, β denotes the full width half maxima (FWHM) of the peaks, θ is the Bragg's angle, λ represents the wavelength of the Cu- α radiation (1.5406 Å), D is the crystallite size, ϵ is used for micro-strain present in the samples.

The results obtained from W-H plot studies (Fig 3 (d,e)) have shown that the crystallite size of the pure YF sample comes around 33 nm with the micro-strain of 1.37×10^{-3} . Whereas, the crystallite size and strain are found to be 35 nm and 5.24×10^{-3} respectively, for YGF. The results obtained from W-H plots are tabulated in Table 2. It has been noticed that the strain values along with crystallite size have got increased on changing the crystal structure from YF to YGF as their corresponding crystal structures also got transformed from orthorhombic to cubic. This rise is majorly accommodated due to the occurrence of more structural distortions which is majorly due to more fluctuations in the bond lengths (as can be observed in Table 3). Fig 3 (f,g) represents the crystal structures for both samples which is obtained using VESTA software or by employing the use of Rietveld refined files of each samples from FULLPROF suite software. Some crucial parameters such as lattice parameter, X-ray and bulk densities, Porosity (%), Crystallinity (%), dislocation density have been calculated and are given by the chemical formula as follows: (shown in equations 3-8):

$$\text{Lattice parameter (a)} = d\sqrt{h^2 + k^2 + l^2} \quad (3)$$

$$\text{X-ray density } (\rho_x) = \frac{8M}{Na^3} \quad (4)$$

$$\text{Bulk density } (\rho_b) = \text{Mass of pellet} / \text{Volume of pellet} \quad (5)$$

$$\text{Porosity (\%)} = 1 - \rho_b / \rho_x \quad (6)$$

$$\text{Crystallinity \%} = \frac{\text{Area obtained under the crystalline peaks}}{\text{Area of all peaks}} \times 100 \quad (7)$$

$$\text{Dislocation density} = 1/D^2 \quad (8)$$

where d is the interplanar lattice spacing, $(h\ k\ l)$ represents the miller indices, β is the FWHM, θ is the Bragg's angle, λ is the wavelength of Cu-K α radiations which is equal to 1.54 Å.

Table 2. Enlisted values of residual factor (R_p), Weighted residual factor (R_{wp}), and goodness of fit (χ^2), X-ray density (D_x), bulk density (D_b), porosity (%), volume of lattice, for the samples YF and YGF, obtained from Rietveld refinement.

Parameters	Compositions	
	YF (YFeO ₃)	YGF (Y ₃ Fe ₅ O ₁₂)
Crystallite size (nm)	33	35
Microstrain ($\times 10^{-3}$)	1.37	5.24
ρ_x (g/cm ³)	5.416	5.14
ρ_b (g/cm ³)	4.50	3.97
Lattice constant (Å)	a = 5.5940 Å, b = 7.6063 Å, c = 5.2828 Å	a = b = c = 12.3821 Å
Dislocation density (δ) (nm ⁻²) ($\times 10^{15}$)	0.9182	0.8163
Cell Volume (Å ³)	224.7837	1898.3918
Porosity (%)	15.09	22.7
Crystallinity (%)	75.690	76.175
χ^2	1.44	2.41
R_{wp}	2.86	3.61
R_p	2.80	2.59

Table 3. Enlisted values of shared octahedral and tetrahedral bond length, unshared bond length, bond angles obtained using refinement of XRD patterns.

Samples	Bond length (Å)				Bond angles (°)		
	Fe-O	Fe-Fe	Y-Fe	Y-O	Y-Fe-O1	Y-Fe-Y	Fe-O1-Fe
YF	2.09330	3.84712	3.07322	2.33796	49.5307	107.3611	50.8571
YGF	3.78402	12.3822	10.3828	2.47947	46.28906	35.2644	48.9341

3.2. Morphology studies

The formation of more porous structured garnet ferrite nanoparticles has been confirmed from the SEM and HRTEM images as shown in Fig 4. SEM images shows that most of the particles are agglomerated together with each other uniformly [Fig 4 (a)]. Presence of pores in the sample are detected which prevents the sufficient diffusion of some atoms onto the surface and results in the formation of stable nanocrystalline powder. Porous structures also signify the breaking of the agglomerations after sintering done at high temperature values [30]. The SAED pattern of the YGF sample is shown in Fig 4(b). The obtained HRTEM images (shown in Fig 4 (c-e) depicted that the YGF nanoparticles when prepared through modified sol-gel route and sintered at 900°C for 4 h produced highly crystalline nanoparticles with their average grain size lies between 40-50 nm. Hence, it further justifies that the YGF nanoparticles prepared using sol-gel synthesis route exposed better morphology with smaller grain size as compared to other synthesis methods. The porous nature of YGF can also be confirmed by the HRTEM images as can be observed in Fig 4 (f-h). Porosity of garnets are comparatively higher than that of normal yttrium ferrites due to formation of less denser garnet ferrite nanoparticles at a particular sintering temperature (as shown in Table 2) [31]. Moreover, the high porous nanostructures will be having more internal surface area and the existence of more active sites

[43]. The existence of these two conditions will give rise to an enhanced oxygen evolution reaction activity. Hence, the YGF in cubic form could lead to produce better OER activity as compared to YF in orthorhombic form. The elemental mapping of all the elements Y, Fe, and O present in the synthesized material (YGF) along with the EDX pattern is shown in the supplementary file, Fig S1.

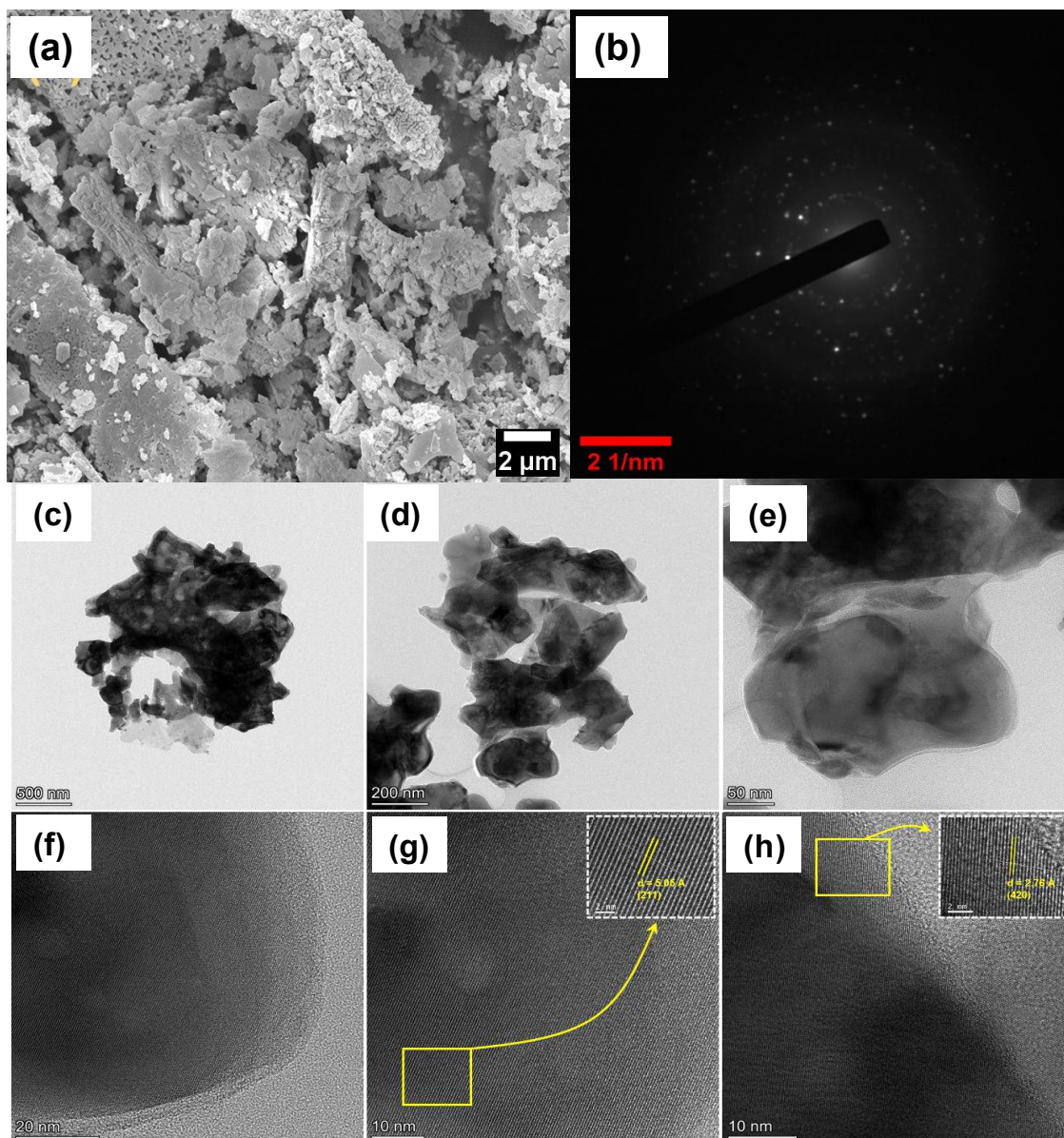


Fig 4. (a) SEM image of the YGF sample, (b) SAED pattern, (c-e) TEM images, and (f-h) HR-TEM images of the YGF sample.

3.3. Vibrational spectroscopy studies

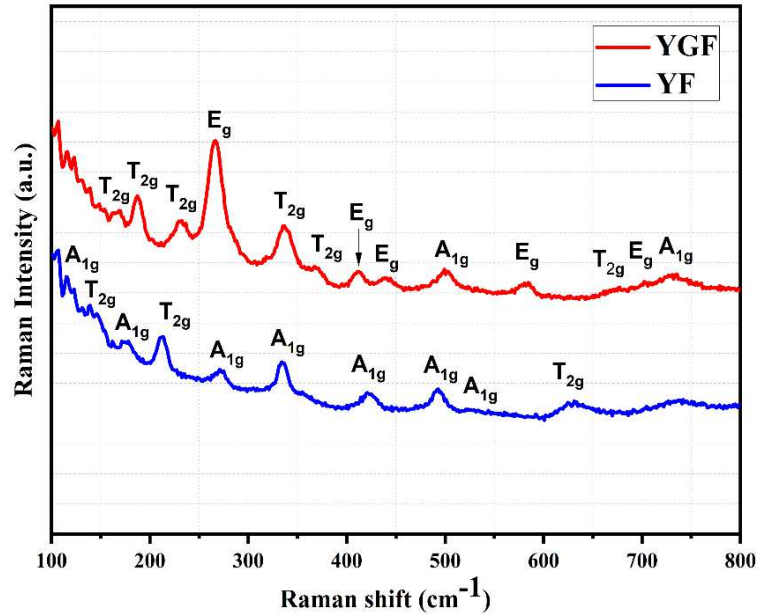


Fig 5. Raman spectra for the prepared ferrites samples using wet chemical synthesis route.

Raman spectroscopy is usually done to verify the presence of crystallinity in the samples since vibrational modes immediately responds to the crystal defects, strain, and concentration of dopants. The Raman spectra for the prepared ferrites has been observed in the wavenumber ranging between 100 cm^{-1} to 800 cm^{-1} as shown in Fig 5. The obtained Raman spectra was recorded by considering a laser light of wavelength, $\lambda = 532\text{ nm}$. The Raman spectra within the wavenumber range (100 cm^{-1} - 800 cm^{-1}) verifies the translation motion of the cations (Fe^{3+} and Y^{3+}) and this similar kind of spectra has also been reported by various researchers. All the 7 A_{1g} modes have been observed for YF sample at wavenumbers 147.11 cm^{-1} , 174.31 cm^{-1} , 272.19 cm^{-1} , 333.89 cm^{-1} , 421 cm^{-1} , 491.22 cm^{-1} , and 523.89 cm^{-1} . The similar results are in concordance with the reported work [31]. However, the vibrations of the Y^{3+} ions are associated at wavenumbers 146 cm^{-1} (T_{2g}) and 178 cm^{-1} (A_{1g}). The Raman peak emerging near wavenumber $\sim 220\text{ cm}^{-1}$ is due to the vibration of Fe^{3+} ions. Other than this, all the low intense peaks coming in the Raman spectra of YF sample near wavenumbers $\sim 272\text{ cm}^{-1}$, 334 cm^{-1} , 420 cm^{-1} , 491 cm^{-1} are assigned due to the excitation of Fe^{3+} ions within the domain of octahedral system. In the garnet ferrite or YGF, there are in total 25 Raman active modes in

the spectra of yttrium garnet ferrites (YGF). These 25 Raman active modes consist of 3 A_{1g} , 8 E_g , and 14 T_{2g} modes in the garnet ferrite sample. The occurrence of T_{2g} and E_g modes at wavenumbers 100 cm^{-1} and 300 cm^{-1} dealt with the translation vibration of Y^{3+} and Fe^{3+} cations in the tetrahedral (FeO_4) and dodecahedral (RO_8) lattice sites respectively. The observed wavenumbers within the wavenumber ranging b/w 400 cm^{-1} and 800 cm^{-1} corresponds to the symmetric stretching of the tetrahedral (FeO_4) and octahedral (FeO_6). The sharp peak present at 267 cm^{-1} can be explained on the basis of Franck Condon principle. According to which, in any electronic transition, significant overlap between two vibrational wavefunctions increases the likelihood of a matching transition from one vibrational energy level to another one [32]. The cations at the tetrahedral and dodecahedral locations of the garnet crystal lattice exhibit a distinctive translational vibration in this vibrational mode.

3.4. Optical Studies

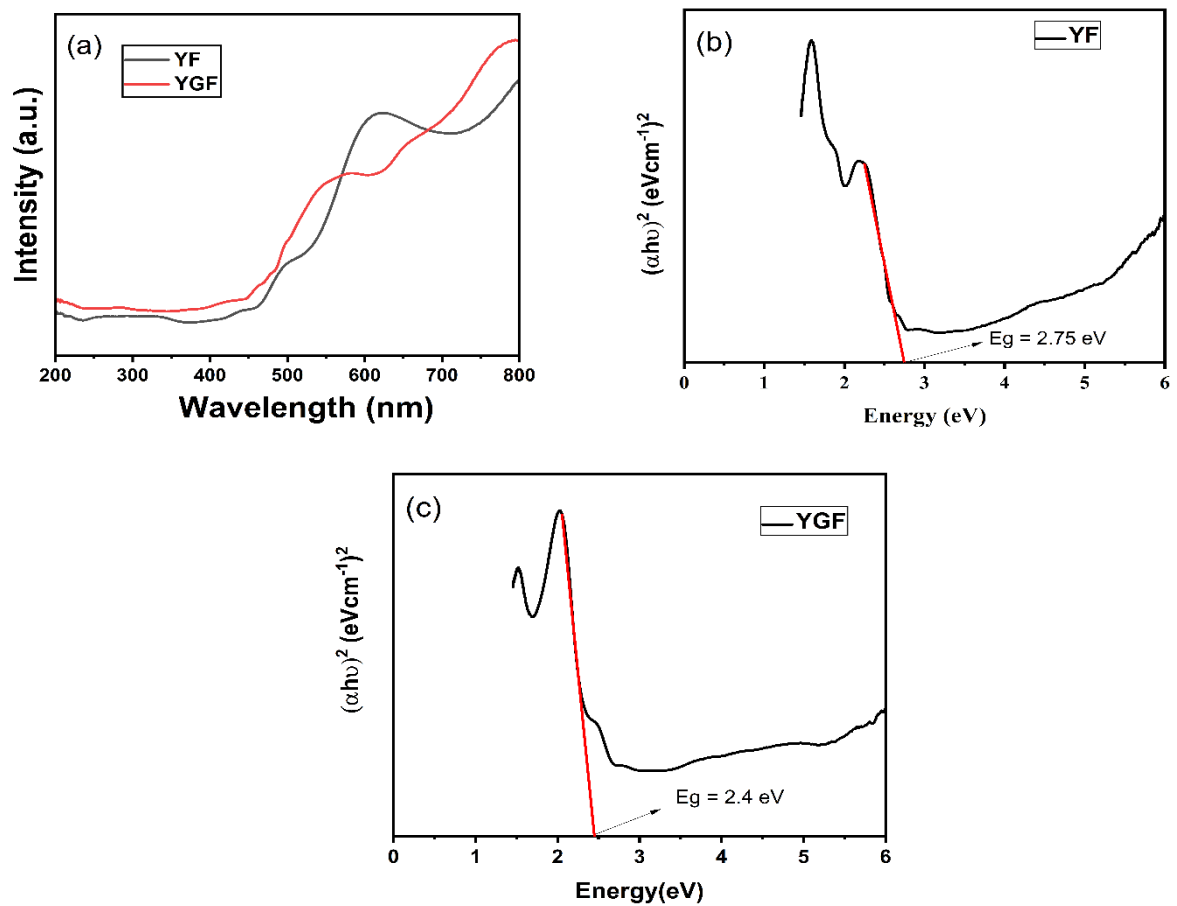


Fig 6. UV-DRS spectra of the samples (a) Intensity vs wavelength, (b-c) Tauc plots for YF and YGF.

The UV-visible studies are conducted to analyse the optical characteristics of YFeO_3 and $\text{Y}_3\text{Fe}_5\text{O}_{12}$ within a wavelength range of 200 nm to 800 nm as shown in Fig 6. The optical bandgap of the as prepared samples has been obtained by using Tauc's relation and plotting $(\alpha h\nu)^n$ against $h\nu$ where n depends on the nature of the electronic transition [33] (as shown in Fig 6 (b,c)).

$$(\alpha h\nu)^n = A(h\nu - E_g) \quad (4)$$

where ν , A , h and E_g denotes the frequency of the incoming light, energy-independent constant, Planck constant, optical band gap, respectively.

In the equation (4), n determines the optical transition type of the material. It can take on the values 2 (indirect) or $\frac{1}{2}$ (direct) depending on the nature of transmission. As can be observed from the obtained Fig 6, bandgap decreased from 2.7 eV to 2.4 eV on changing the crystal structure from orthorhombic to cubic. This decrease in energy gap is mainly due to the creation of additional energy levels due to addition of more yttrium and iron atoms which helps in more transfer of electrons to the conduction band. The obtained bandgap values are found to be consistent with the values as reported in the literature [34].

3.4. Photoluminescence (PL) studies

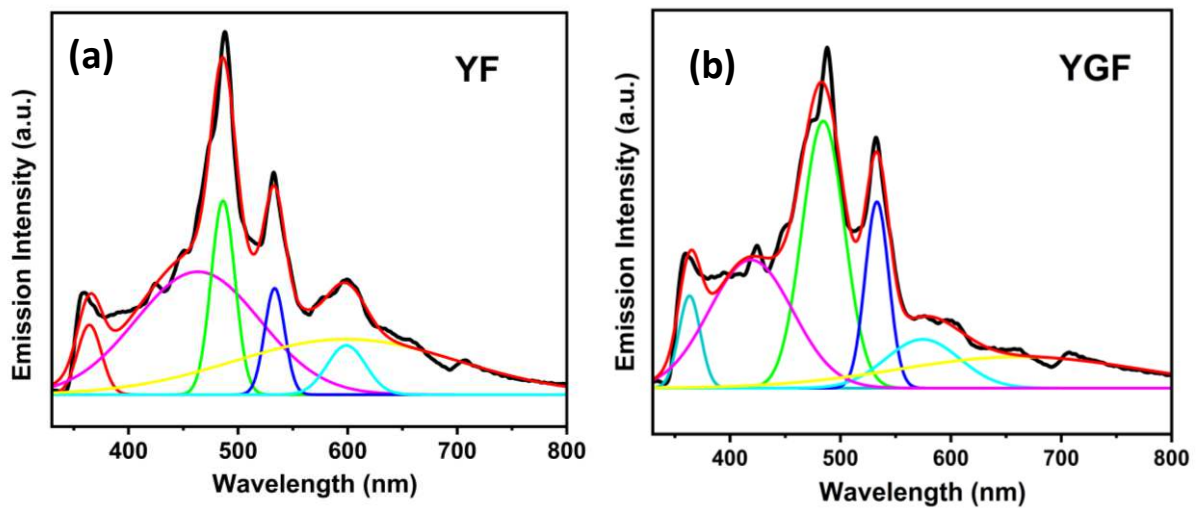


Fig 7. Photoluminescence spectra of the as-prepared (a) YF, (b) YGF nanoparticles.

The photoluminescence (PL) studies of nano-ferrites were conducted to gain insight into the effect of on the energies and of the excited states (as depicted in Fig 7). PL spectra were

acquired at room temperature upon excitation at 450 nm blue light, and emissions were recorded between 500 and 700 nm. The emission bands for the prepared samples (YF and YGF) are shown in Fig 7(a) and Fig 7(b) respectively. The highly intensified emission peak could be observed near wavelength 500-530 nm. This is mainly attributed due to the transition between $4G_{7/2} \rightarrow 4I_{9/2}$, which is observed for both samples [35]. Hence, this confirms the occurrence of green emission taken place in both pure YF and YGF. It is found that the PL intensity band obtained near 500 nm got increased upon changing the crystal structure from orthorhombic (YF) to cubic (YGF) as can be observed from Fig 7 (a,b). The peaks emerging at the wavelength near 500-530 nm are mainly attributed due to the recombination of excitons [36]. The obtained PL spectra is demonstrating the green emission which mainly originates due to the presence of oxygen vacancies present in the sample. Therefore, the prepared samples can also exhibit their promising results in developing various devices such as sensors, photodetectors, hydroelectric cells, supercapacitors, etc [37-39].

3.5. X-ray photoelectron spectroscopy (XPS) studies

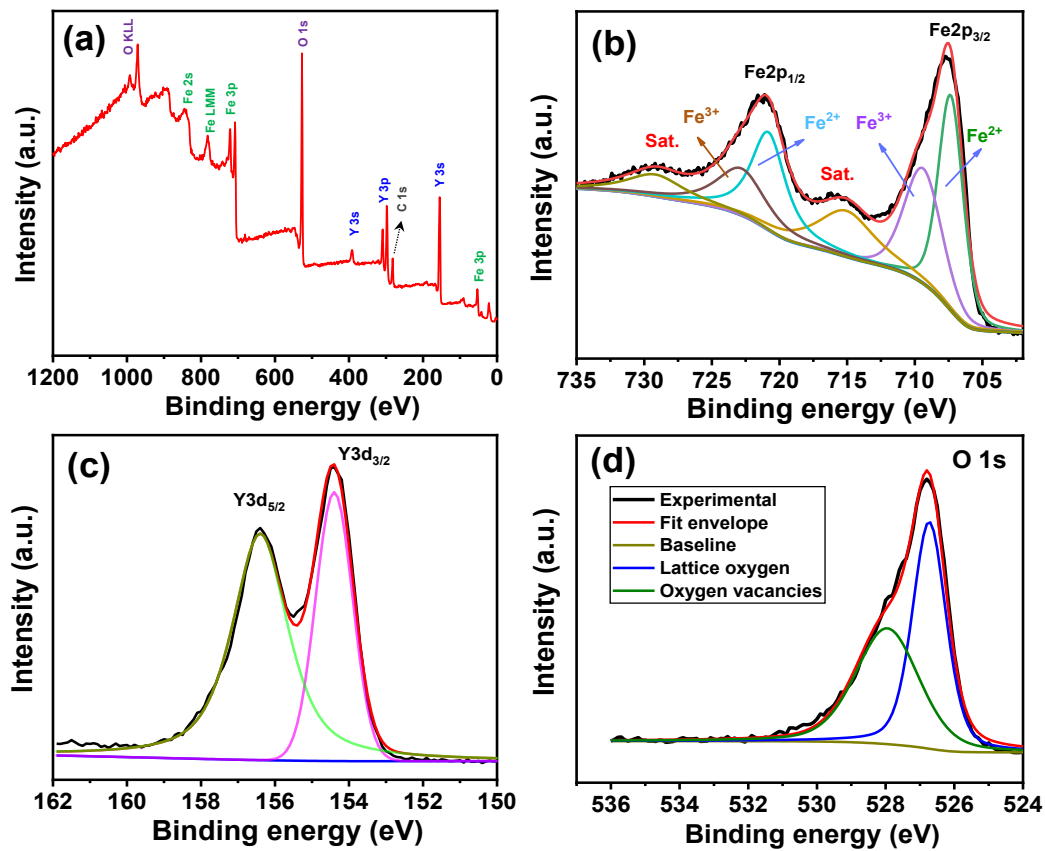


Fig 8. (a) XPS survey spectra of the YGF, Deconvoluted XPS spectra of (b) Fe 2p, (c) Y 3d, and (d) O 1s.

The wide range X-ray photoelectron spectra (XPS) of the prepared sample (YGF) are shown in Fig 8 (a). The as-obtained XPS spectrum depicts the significant characteristic lines of C, O, Fe, and Y elements which further confirms the formation of yttrium garnet ferrites ($Y_3Fe_5O_{12}$). The occurrence of peak at 281.57 eV is attributed due to some carbon impurities which might left behind after preparation of sample. Fig 8 (f) displays the $Fe2p_{1/2, 3/2}$ XPS spectrum at the binding energies of 707.68 eV and 721.05 eV. The $Fe 2p_{3/2}$ is deconvoluted into 2 peaks (709.56 eV and 707.37 eV) exhibiting multiple Fe^{3+} oxidation states as explained in a similar way by many researchers [40]. The satellite peaks are located at the binding energy of 715.27 eV and 729.41 eV corresponding to $Fe 2p_{3/2}$ and $Fe2p_{1/2}$. Fig 8 (g) depicts the existence of $Y3d_{3/2, 5/2}$ occurs within the binding energies of 150-160 eV and it is coinciding with the result reported by M. Yousaf et al. [41]. Fig 8 (h) shows the XPS deconvoluted spectra of O1s spectra for YGF sample and hence this spectrum can be considered as the sum of two peaks, mainly first one (which is due to the presence of oxygen ions in the lattice) at 526.72 eV and the second one (is due to the generation of oxygen vacancies due to the lattice expansion) at 527.99 eV [42].

3.6. Brunauer Emmett Teller (BET) studies

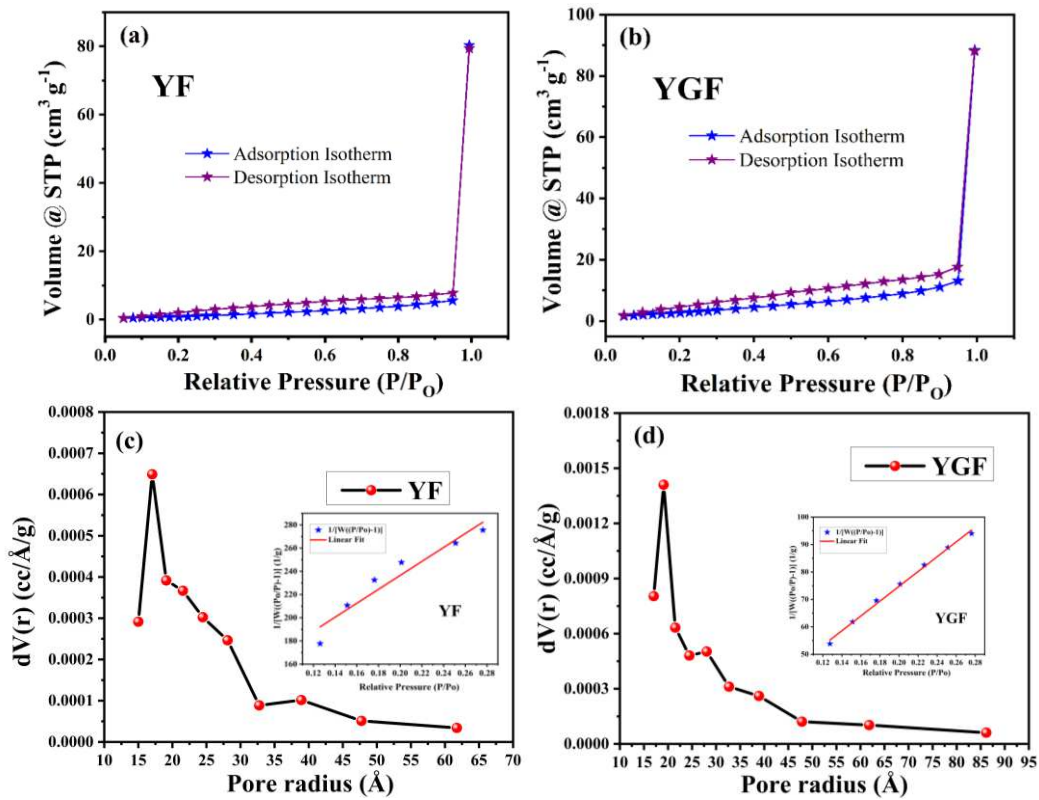


Fig 9. BET N₂ adsorption/desorption isotherm plots for (a) YF, (b) YGF. Pore size distribution curves of (c) Y₃Fe₅O₁₂, (d) YFeO₃ [The insets contain BET surface area equation plots],

N₂ adsorption-desorption studies were conducted at 77.35 K to determine surface area, pore size distribution and pore volume for the synthesised samples. BET isotherms are depicted in Fig 9 (a, b) and exhibits hysteresis loop at a relative pressure (P/P_0) close to unity. This isotherm is classified as a type IV isotherm by the IUPAC nomenclature. According to the BET isotherms YFeO₃ and Y₃Fe₅O₁₂ has a specific surface area of 6.067 m²/g and 12.815 m²/g (Fig 9 (c, d)) respectively. The observed surface area was comparable to the values reported in the previous studies [43-45]. Y₃Fe₅O₁₂ showed better surface area than YFeO₃ because it shows the BJH pore size distribution, which ranges from 10 to 90 Å. Pore volume for the samples YF and YGF was determined to be 0.008 cm³/g and 0.018 cm³/g respectively (as shown in Table 4). The pore radius was found to be 1.70 nm for YF and for YGF it was 1.91 nm. These results suggest the existence of microporous nature (< 2nm) of the synthesized samples. These results correlate well with the XRD and FESEM results as well. In particular, the XRD analysis (Fig. 3) shows that YGF develops crystallites of a cubic Ia-3d space group, which is highly ordered with a certain degree of structural distortion and micro-strain (5.24×10^{-3}) is induced in comparison to YF (1.37×10^{-3}). These distortions create lattice defects and vacancies, facilitating higher pore formation and improved adsorption sites, leading to enhanced BET surface area. Furthermore, the SEM and HRTEM images (Fig. 4 (a)) support the existence of porous structure in YGF, which is indispensable to enhance its surface area.

Both the large surface area as well as the high porosity of YGF is expected to have a distinct effect on its OER performance. Better surface area relates to greater number of electrochemical reaction active sites, and expansion of pores assists in the swift penetration of the electrolyte, which enhances ease of ion transport. Moreover, the microporosity of YGF enhances the charge transfer even further and thus, better OER performance [46,47].

Table 4: Specific surface area, pore volume and pore radius of YF and YGF.

Composition	Specific Surface Area (m ² /g)	Pore Volume (cm ³ /g)	Pore Radius (Å)
YFeO ₃	6.067	0.008	17.042

$\text{Y}_3\text{Fe}_5\text{O}_{12}$	12.815	0.018	19.101
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3.7. Electrical studies

3.7.1 Dielectric studies of orthorhombic phase of yttrium ferrite (YFeO_3)

The measurement of the dielectric permittivity against frequency (1 Hz- 10 MHz) for the orthorhombic yttrium ferrite is obtained at various temperature values (50°C, 100°C, 150°C, and 200°C) as shown in Fig 10 (a). It has been observed that with the rise in frequency values, the corresponding values of ϵ' gets decreased. It is noticed that near the higher frequency side, the reduction in ϵ' values occurs which is due to the effect of dielectric relaxation [48]. Whereas, the decrement in the lower side is attributed due to the space charge polarization. With the rise in temperature, the ϵ' values got increased slowly due to the existence of space charge polarization. Fig 10 (b) represents the variation of tangent losses against frequency with temperature varying from 50°C to 200°C for both YF and YGF respectively. The tangent loss values of the pure YF have substantially decreased from 1.6 to 0.4 with the rising temperature which indicates the existence of “negative temperature coefficient of dielectric loss (NTCDL)” [49]. As the temperature increases, the Fe^{2+} or Fe^{3+} charge carrier gain enough thermal energy and become more mobile which reduces their contribution to dielectric loss and hence leads towards lower $\text{Tan}\delta$ values at high values of temperature. Fig 10 (c) shows the variation of imaginary values of impedance (Z'') against the real value of impedance (Z') considered at different temperature values. With the help of Fig 10 (c), we can clearly justify the contribution of grain and grain boundaries on the complex value of impedance. The grains are active in the higher frequency regime, whereas the grain boundaries are found to more dominant in the lower frequency areas. With the increase in temperature, the impedance values for both YF and YGF samples got reduced which suggests an enhancement in charge transfer mechanism with the rise in temperature. The Cole-Cole plots helps us to intricate the contribution in conductivity from grain as well as grain boundaries which is calculated in the next sections.

The variation in Z'' values against frequency varying from 1 Hz to 10 MHz with temperature ranging from 50°C to 200°C is shown by Fig 10 (d). As temperature is increased, the peaks shift towards the higher frequency side which is due to the rise in the mobility of immobile ions at higher temperature values. The overall effect results in the peak broadening and

occurrence of electrical relaxation phenomena [48]. This relaxation phenomena is generally utilized in the fast switching devices working under high electric fields. Fig 10 (e) exhibits the fitted Cole-Cole plot of the YF sample obtained at the room temperature. The fitted parameters have been tabulated in the Table 7.

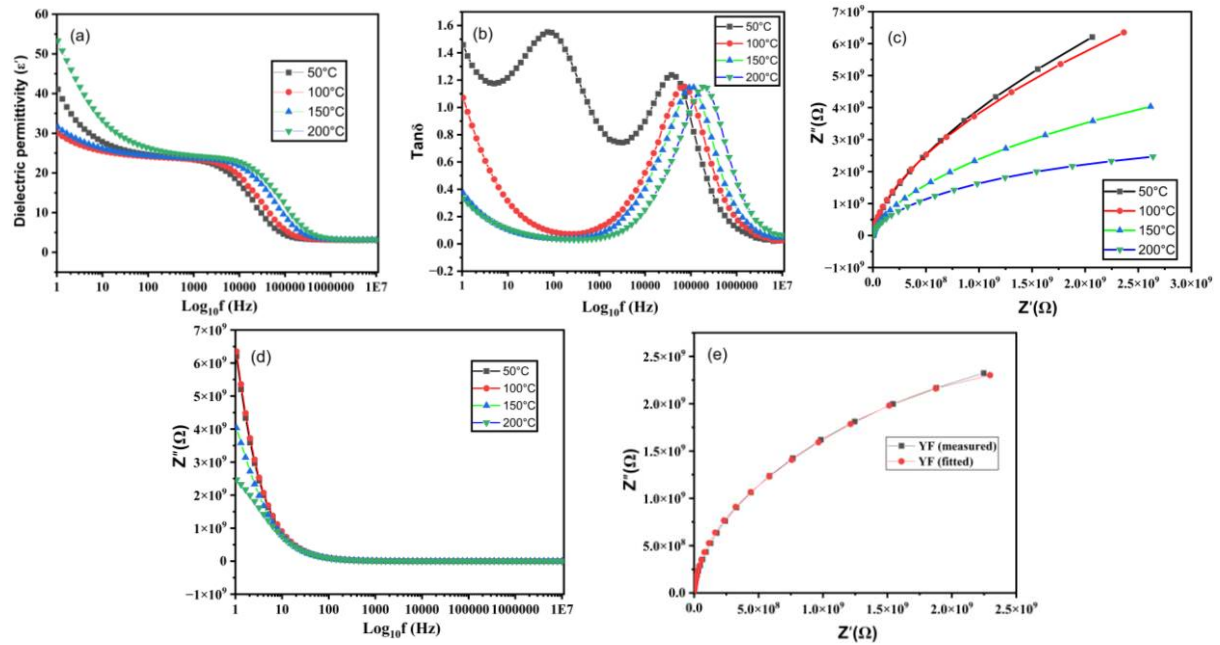


Fig 10. Dielectric studies of YF with varying frequency and temperatures, (a) Plot of dielectric permittivity (ϵ') against frequency, (b) Variation of tangent losses with $\text{Log}_{10}f$, (c) Cole-Cole plots at different temperature values, (d) Plot of Z'' against frequency, and (e) Fitted Cole-Cole plot at lowest temperature limit for pure YF samples.

3.7.2. Dielectric studies of cubic phase of yttrium garnet ferrite ($\text{Y}_3\text{Fe}_5\text{O}_{12}$ or YGF)

In a similar manner, the dielectric studies for the yttrium iron garnet or YGF have been done and shown in Fig 11 (a-e). The similar variation of dielectric permittivity (ϵ') has been demonstrated here as in the sample YF. However, much higher values of dielectric permittivity ($\epsilon' \sim 52$) has been obtained at the lowest temperature (as shown in Fig 11 (a)). This is because the YGF possess a complex cubic structure which allows more polarizability due to the presence of Fe-O polyhedral networks and contains more Fe^{3+} ions, which contributes to a strong polarization effect [49, 50]. Fig 11 (b) exhibits the variation of tangent losses against the frequency with the rising temperatures from 50°C to 200°C. It is observed that the losses are increasing with the subsequent rise in the value of temperatures. Whereas, Fig 11 (c) shows the typical Cole-Cole behaviour persisting in the garnet ferrites. A formed semi-circular arc

denotes the presence of both grains and grain boundaries in the samples and the corresponding fitted Cole-Cole plot is shown in Fig 11 (e). Fig 11 (d) shows the variation of Z'' against the frequency for different values of temperature. Considering all aspects related to dielectric studies, it has been concluded that the YGF has exhibited more improved dielectric behaviour as compared to the sample YF. More improved dielectric constant can enhance charge separation and transport of charge carriers which together will improve the overall OER performance [50]

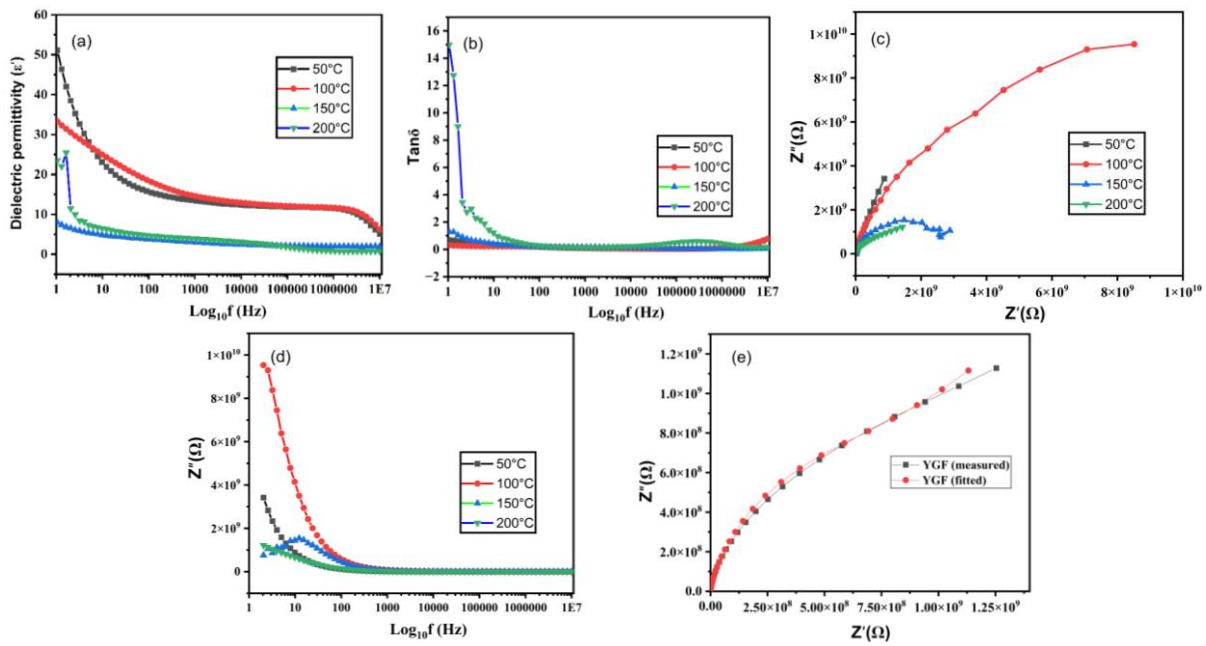


Fig 11. Variation of (a) ϵ' against $\text{Log}_{10}f$ (Hz) at the different temperatures, (b) Tangent loss against frequency, (c) Cole-Cole plots, (d) Z'' against frequency, and (e) Fitted Cole-Cole plot for the YGF nanoparticles.

3.7.3. Comparison of the dielectric studies done at room temperature

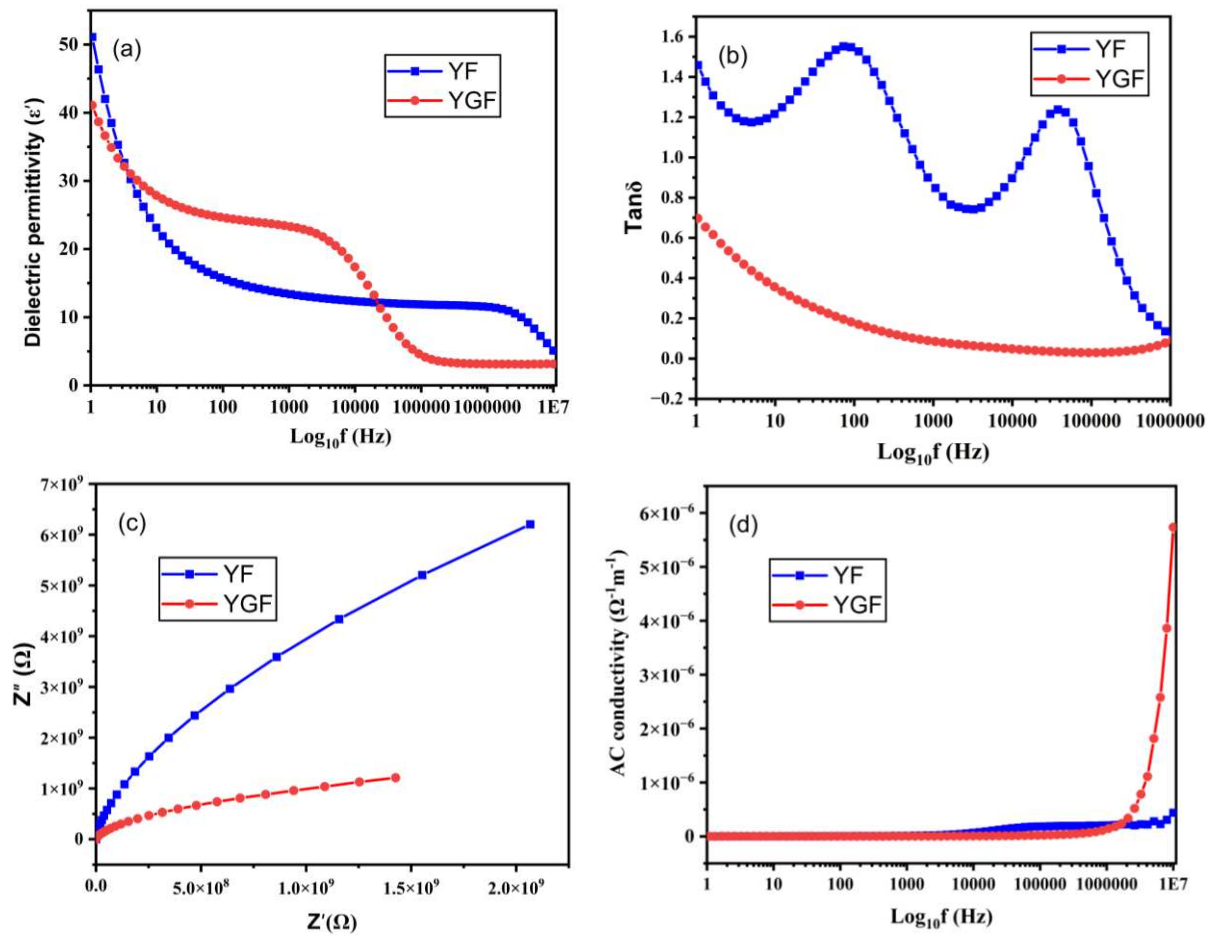


Fig 12. (a) Variation of ϵ' against frequency for yttrium ferrite and garnet ferrite at room temperature, (b) Comparison of $\text{Tan } \delta$ against frequency, (c) Cole-Cole plots for pure YF and YGF, and (d) AC conductivity against frequency for YF and YGF.

Fig 12 (a) deals with the room temperature variation of the ϵ' of YFeO_3 (YF) and $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YGF) against frequency varying from 1 Hz to 10 MHz. It has been observed from the plots that the ϵ' of YGF is greater than the ϵ' of pure YF which means that the garnet ferrite keeps the more ability to store the charge as compared to yttrium ferrite in orthorhombic form. Whereas, Fig 12 (b) depicts the comparative variation of tangent losses in both pure YF and YGF. The obtained variation concludes that the garnet ferrite contains minimum tangent loss as compared to the yttrium orthoferrite at room temperature, which further means that YGF dissipates less heat and would be able to store more charge with minimum power loss. Fig 12 (c) exhibit that the YF samples are highly resistive as compared to the YF samples, which

further concludes that the YGF sample's conductivity is more than the conductivity of YF sample. In this way, it can be concluded that YGF sample has exhibited the better electrical properties as compared to the YF samples. Furthermore, Table 5 and Table 6 enlist the values of dielectric permittivity and tangent losses for both YF and YGF samples at different temperature values. It is observed that the permittivity values found to be high for YGF and its value is increasing with the increasing temperature which thereby concludes the thermal activated hopping of charge carriers [51,52]. The Cole-Cole plots for YF as well as YGF at room temperature has also been fitted using equivalent RC circuit and the equivalent fitted parameters are tabulated in the Table 7.

Table 5. Enlisted value of real values of permittivity (ϵ') for the prepared composition at different temperature values.

Sample	Values of ϵ' at different values of temperature, 1 KHz			
	T = 50°C	T = 100°C	T = 150°C	T = 200°C
YF	13.125	14.292	2.863	3.738
YGF	23.200	23.398	23.677	24.314

Table 6. Enlisted value of real values of dielectric loss tangent ($\tan\delta$) taken at different temperature values.

Sample	Values of $\tan\delta$ at different values of temperature, 1 Hz			
	T = 50°C	T = 100°C	T = 150°C	T = 200°C
YF	1.461	1.074	0.379	0.331
YGF	0.765	0.285	1.326	14.964

Table 7. Fitted values of Cole-Cole plots for the prepared samples (YF and YGF)

Sample	Temperature (°C)	$R_g (\Omega)$	$CPE_g (F)$	n_g
YF	50	2.4×10^9	3.428×10^{-9}	0.86
YGF	50	1.20×10^9	5.761×10^{-9}	0.92

3.8. Oxygen Evolution Reaction (OER) studies

The OER performances of YF and YGF catalysts were performed by carrying out linear sweep voltammetry (LSV) measurements in a three-electrode setup using 1 M KOH solution as electrolyte, details experimental procedures are described in the supporting information file. The LSV plots showed that YGF exhibited the lowest overpotential of 392 mV than that of YF catalyst (517 mV) to achieve the same current density of 10 mA/cm² (Fig 13 (a)). In addition, the onset potential of YGF (1.47 V vs. RHE) is also lower compare to YF (1.53 V vs. RHE). To estimate the OER kinetics of the present catalysts, the Tafel slopes were calculated from their respective LSV curves as shown in Fig 13 (b). The Tafel slope of YGF was calculated to be 133 mV/dec which was much impressive than that of YF (218 mV/dec) for OER performance. The electrochemical impedance spectroscopy (EIS) was studied at an overpotential of 420 mV over potential in 1.0 M KOH ionic solution to get the charge transfer resistance (R_{ct}) across the electrode and the electrolyte interface during OER performance as depicted in Fig 13 (c). The R_{ct} values of YGF and YF were found to be 359 Ω , and 905 Ω respectively. The stability of a catalyst is also a crucial factor during the fabrication of a suitable electrocatalyst for the anode material (Table 8). We have performed the chronoamperometric stability test at applied overpotential of 392 mV and after 24 h a current density of 9.5 % was lost which reflected a superior durability of YGF catalyst for electrochemical OER activity (Fig 13 (d)). We have also calculated the electrochemical active surface area (ECSA) by performing scan rate dependent CV in non-faradic region of the all-present catalysts as shown in Fig 14. The highest electrochemical double-layer capacitance (C_{dl}) and the corresponding ECSA was found to be 0.73 mF/cm², and 18.25 cm² for YGF, respectively. YF showed C_{dl} and the corresponding ECSA value of 0.57 mF/cm² and 14.25 cm². Notably, the ECSA normalised LSV analysis confirms the intrinsic characteristics of YGF for the best OER performance in alkaline medium (Fig S7). Summarizing, materials with high value of interfacial capacitance tend to reduce charge transfer resistance and facilitating faster OER kinetics. From the conducted dielectric studies, it has been shown that sample YGF exhibit lower dielectric loss at high frequencies as compared to YF. Less dielectric loss means better electronic conductivity, which also leads to lowering the overpotential value for OER activity of YGF catalyst.

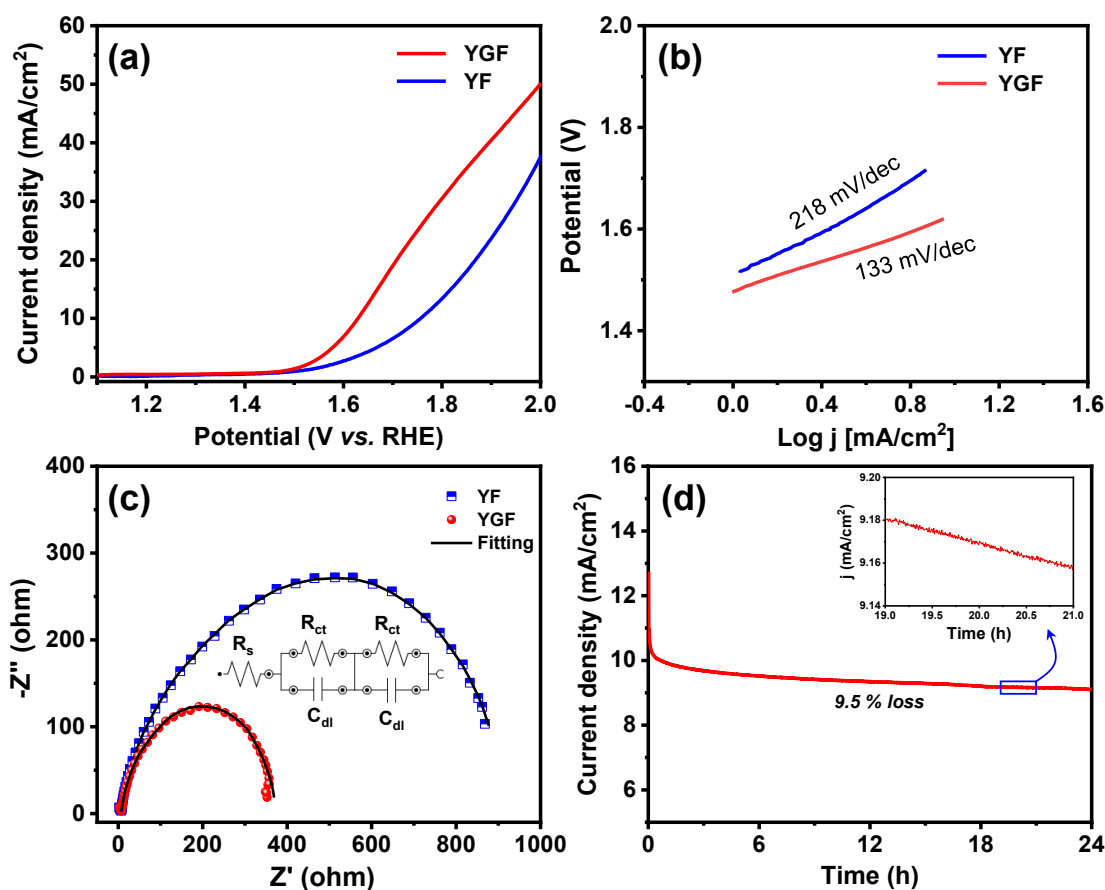


Fig 13. (a) Represents the linear sweep voltammetry (LSV) and (b) corresponding Tafel slope of YF and YGF catalysts in a 1 M KOH electrolyte solution ($\text{pH} = 13.8$). (c) Electrochemical impedance spectra of the present catalysts at an applied overpotential of 420 mV. (d) Chronopotentiometric stability plot of YGF catalyst at applied overpotential of 392 mV for the OER.

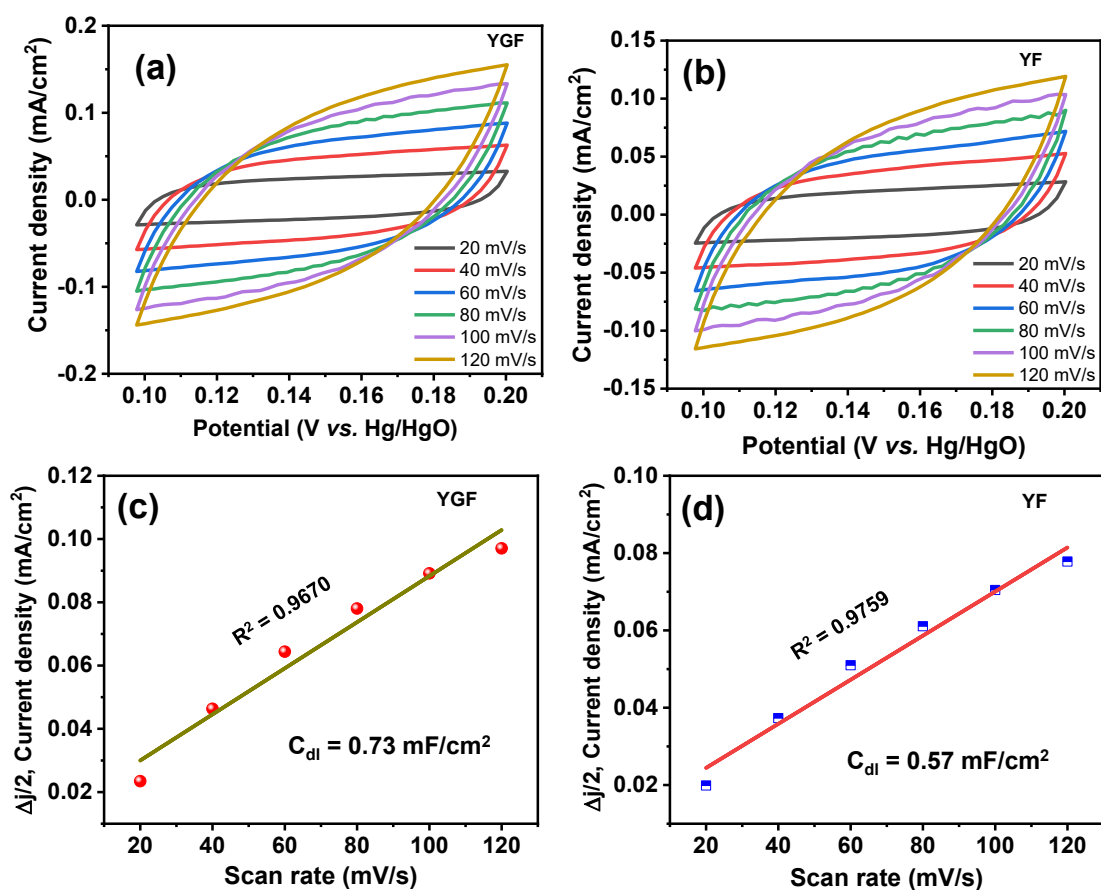


Fig 14. Cyclic voltammetry curves of (a) YGF, (b) YF. (c) and (d) represent the corresponding plot of $\Delta j/2$ vs. scan rate for the determination of double layer capacitance (C_{dl}) in 1 M KOH electrolyte solution (pH = 13.8).

Table 8. Summarization of OER Performance of pure yttrium orthoferrites and yttrium garnet ferrites.

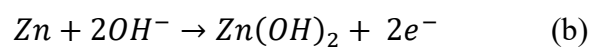
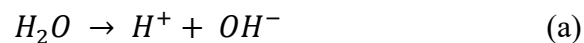
Catalysts	Overpotential (mV) at 10 mA/cm ²	Tafel slope (mV/dec)	R_{ct} (ohm)	C_{dl} (mF cm ⁻²)	ECSA (cm ²)
YF (YFeO ₃)	517	218	905	0.57	14.25
YGF (Y ₃ Fe ₅ O ₁₂)	392	133	359	0.73	18.25

3.9. Hydroelectric cell studies

The Hydroelectric cells (HEC) of the both samples have been fabricated by following the conventional approach as we have usually done in our previous works [53, 28] and the following schematic representation for the preparation of the cells is shown in the supplementary file (**Fig S3**). After preparing the HEC, water is sprinkled on the surface of the cells using a dropper (more specifically 20 μ L of DI water). Instantly, water started adsorbing on the sample surface and generated significant value of current which can be measured by the digital multimeter (Hioki DT4252). The maximum values of the short circuit current as well as the open cell voltage has been recorded and enlisted in Table 9. After going through the maximum current and voltage, the V-I polarization curves for the prepared cells was measured using the Keithley 2450 source meter.

3.9.1. Working Mechanism in the HECs

The mechanism of water splitting is involved in the functioning of HECs, where the process is first initiated when a water molecule comes in contact with the oxygen-deficient sample's surface. The unsaturated surface cations (Lewis acid) such as Y^{3+} , Fe^{2+} , Fe^{3+} will first interact with the lone pair electrons of oxygen (which act as Lewis Base) contained in the water molecule [54]. The interaction between these two entities will weaken the HO-H bond which will ultimately lead to the dissociation of the water molecule into H^+ and OH^- ions. This process will lead to the formation of first chemisorbed layer of OH^- ions and through hydrogen bonding, it will bind more water molecules (creating the physisorbed layer). Afterwards, the hopping of protons will occur in the physisorbed layers, and during this process, these ions got trapped inside the nanopores present on the sample's surface. This trapping of hydronium ions will generate enough electric potential to further break the water molecules present in the physisorbed layers. At zinc anode, the OH^- ions will be collected after migrating through the oxygen vacancies and hence the oxidation of zinc takes place to form zinc hydroxide and releasing two electrons which will flow from zinc (anode) to silver (cathode), generating the net electrical output (shown in the equations a-c):



3.9.2. *V-I polarization curves of the prepared HEC*

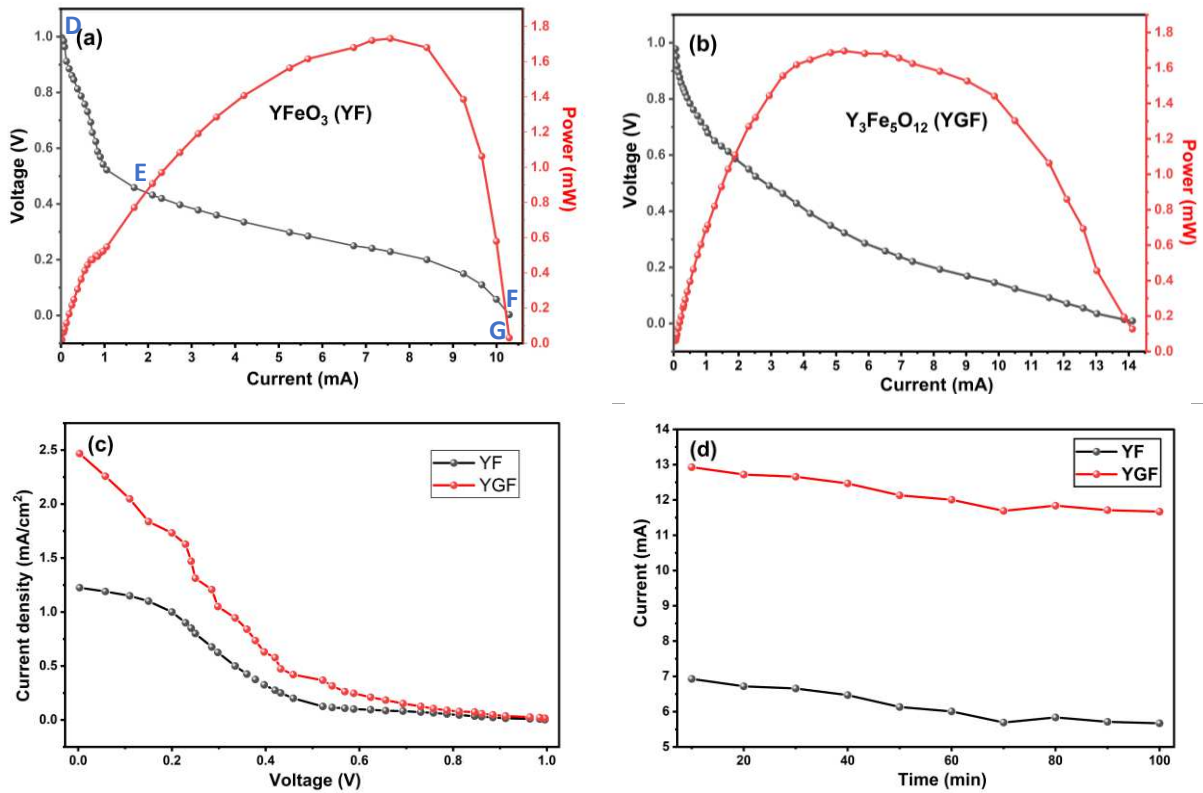


Fig 15. (a-b) V-I curves for the YF and YGF, (c) Variation of current density vs voltage (V), (d) Stability (current vs time) plots for the YF and YGF based HECs.

The measurement of current and voltage values have been done using V-I polarization curves as shown in Fig 15 (a-d). The plots obtained in the Fig 15 were obtained by varying the load connected to the cell and plotting the variation of voltage drop against the rise in the current values. The curve is mainly divided into the three main regions: Activation losses, ohmic losses, and mass concentration losses. The short circuit current as well as open circuit voltage for YF and YGF were recorded as 10.300 mA, 0.991 V; 14.123 mA, 0.981 V respectively (enlisted in Table 6). The point D shows the maximum offset voltage by the prepared HEC. However, the region DE is attributed to the activation losses which is faced by the dissociated ions due to the formation of barrier [55]. For the prepared cells of YF and YGF, the activation losses were found to be 0.398 V (YF) and 0.337 V (YGF). This observation concluded that the garnet ferrite sample (YGF) exhibits a comparatively lower activation loss as compared to that of yttrium orthoferrites (YF) and this lower activation potential will cause the fast dissociation of water molecules on the surface of YGF and ease the transportation of the ions

towards the respective electrodes. The linear portion EF (showing in Fig 15 (c)) indicates the ohmic losses present in the sample due to presence of internal resistances [56]. Whereas, the region FG is known as “mass concentration loss” attributed due to the abundant concentration of ions near the surface of electrodes [57].

Table 9. Enlisted values of short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum peak power (P_{max}), Current density (J), and mass concentration loss (ΔV_m).

HECs	I_{sc} (mA)	V_{oc} (V)	P_{max} (mW)	J (mA/cm ²)	ΔV_m (V)
YF	10.300	0.991	10.207	2.575	0.084
YGF	14.123	0.981	13.854	3.530	0.029

3.10. Post measurement studies

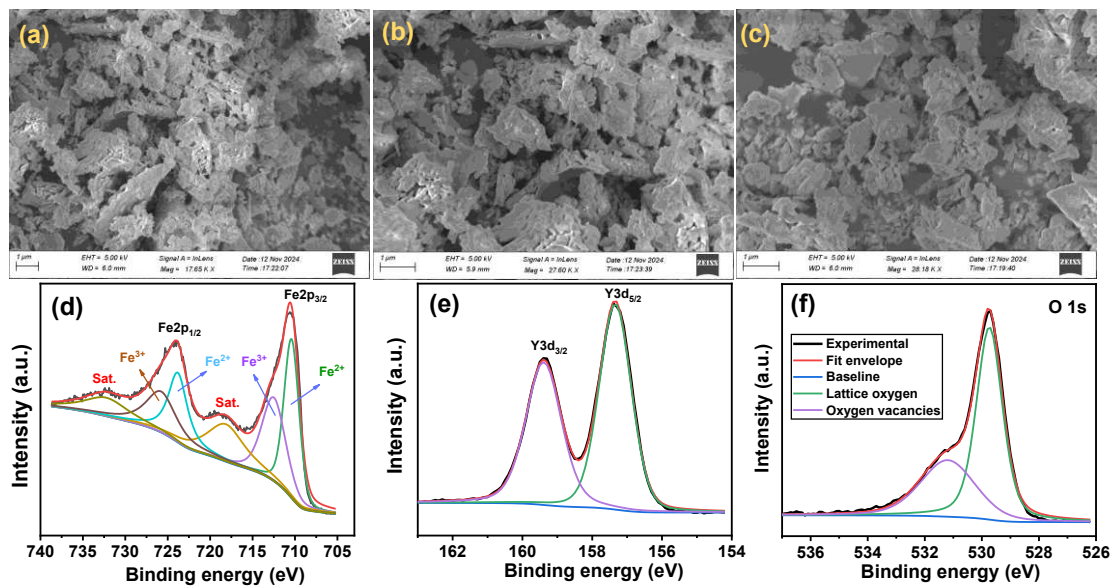


Fig 16. (a-c) SEM images of the sample YGF after OER stability test, (d-f) Post catalytic XPS measurements of the yttrium garnet ferrite.

After processing prolonged OER studies, the structural and surface chemical stability analyses of the YGF electrocatalyst has been done using post-catalytic SEM and XPS measurements as shown in Fig 16 (a-f). The post-catalytic SEM images (as shown in Fig 15 (a-c)) reveals that the catalyst retains its original morphology even after performing OER measurements. The

persistence of the morphology of the particles indicates good mechanical and chemical stability of the YGF catalyst under alkaline OER conditions. However, only minor surface roughening can be observed, which may be associated with surface reconstruction during the electrocatalytic process and the formation of additional active sites. The Fe 2p XPS spectrum shows the coexistence of Fe^{2+} and Fe^{3+} species together with characteristic satellite peaks, confirming the preservation of the mixed-valence iron environment after electrocatalysis. The Y3d spectrum exhibits well-defined Y 3d_{5/2} and Y 3d_{3/2} peaks without significant changes, suggesting the stability of the yttrium framework. Furthermore, the O1s spectrum consists of lattice oxygen and oxygen-vacancy-related components, indicating the retention of oxygen defect sites that are beneficial for OER kinetics. These results collectively demonstrate the excellent structural and chemical stability of the YGF electrocatalyst under alkaline OER conditions.

4. Conclusion

Summarizing, we have successfully prepared yttrium orthoferrites (YF) and yttrium iron garnets (YGF) nanoparticles using modified sol-gel auto combustion wet chemical synthesis route and investigated their structural, morphological, impedance, and dielectric studies for electrochemical OER performance. The formation of structure of both samples have been confirmed from HRXRD, FTIR, and Raman spectroscopy. Whereas, the morphology of the obtained nanoparticles has been confirmed from the SEM and HRTEM studies which revealed that the prepared ferrites are in nanosized form. The optical studies of the prepared NPs have been also conducted and it was found that the bandgap values reduced from 2.7 eV to 2.4 eV (for YGF) as revealed from UV-DRS spectroscopy. The conducted XPS and BET studies revealed the existence of maximum number of oxygen vacancies in the sample YGF as compared to the YF which proves that YGF has more active sites for adsorption which would lead towards faster OER kinematics. The dielectric studies demonstrated the maximum values of ϵ' , minimum loss, and minimum resistances for the sample YGF which also played a critical role in OER by enhancing active sites and conductivity. The OER studies as well as the HEC measurements yielded the similar conclusions. Both measurements yielded that the sample YGF is the best electrocatalyst due to presence of more oxygen vacancies and more porous nanostructures. The conducted post SEM and XPS measurement studies demonstrated the structural and chemical stability of the prepared samples.

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