Structural and ferri-magnetic features of the nano-crystalline Mn$_{0.5}$Cd$_x$Sr$_{0.5-x}$Fe$_2$O$_4$ nanoparticles

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Abstract. The as-prepared Mn$_{0.5}$Cd$_x$Sr$_{0.5-x}$Fe$_2$O$_4$ nanocrystals, ($x = 0, 0.1, 0.2, 0.3, 0.4, 0.5$), were synthesized by the one-beaker and smart co-precipitation strategy, thereafter nanocrystals were well-characterized by X-ray diffraction (XRD), FT-IR spectra, higher resolution transmission electrons microscopy (HTEM) and vibrating Nano-samples magnetometry (VSM) strategies. XRD investigation proved the evolution of the single-phase spinel structure for all nano-spinels. The crystallite size $R$ values ranged from 16.05 – to – 32.1 nm, with declining behavior with Cd$^{2+}$ cationic ratio $x$. FT-IR absorption spectrum displayed 6-absorption bands that were related to their principle sites and main bonds. The elicited parameters were influenced by the Cd$^{2+}$ cations replacement instead of Sr$^{2+}$ cations. Magnetic merits proved the soft-magnetic features for all these nanocrystals, whereas, all the magnetic parameters were influenced by the replacement process with Cd$^{2+}$ cations. HTEM images exhibited aggregations in these ultrafine nanoparticles. The nanoparticles sizes $Z$ ranged from 20 – to – 35 nm a little greater compared with crystallite sizes $R$.

1. Introduction

The soft-magnetic Nano-spinels have enticed a considerably larger interest amongst the scientific, industrial and technological approaches; this is imputed to their marvelous and sensitive spectral, structural, electrical, thermal and magnetic features. As a consequence, these splendid new ultrafine structures of such Nano-spinels are ultimately the most candidate systems for utilization in versatile expanding numbers of vital and sensitive medical and technological prospects; including NTC thermistors, hyperthermia, magnetically guided anti-cancer drugs, magnetic biosensing, magnetic resonance imaging techniques (MRI), magneto-caloric & magnetic refrigeration's, Ferro-fluids, satellites communications and microwave devices as well as the theranostic implementations of nanoparticles in medicine [1-10]. Nano-spinels provided spectacular structural, electrical and magnetic merits when compared to their bulk similitudes. These merits are varying with sorts and valence state of dopant cations; their radius and discriminative accommodation positions amongst A- and B-sites, synthetic route and thermal handling [11,12]. Synthesizing Nano-spinels are incessantly the arising focus of most up-to-date scientific researching aspects jointly from the synthesizing, characterizing and technical utilization points of view. Scientific efforts in Nano-spinels have solicitude towards several aspects like: synthesis, physical investigation and exploration of new nanomaterials. Investigations of spinels in the nano-size regime has great relevancy to various multidisciplinary approaches. Thence, they include storage and retrieval of data and pigments [13,14]. The potency of Nano-spinels in fields like information storage, telecommunication technology and photo-catalysis is gradually increasing due to the elicited elegant structural and magnetic merits of nanoparticles [15,16].

It is eminent that both Cd$^{2+}$ and Sr$^{2+}$ cations entirely conquer A-sites in Nano-spinels [11], while Fe$^{3+}$ cations could conquer both A- and B-sites [17]. The surge in numbers of Cd$^{2+}$ cations amongst A-sites stimulates the motivation of Fe ions into B-sites, which in turn induces the variations in their various features impacting cationic occupations within these Nano-spinels. Thus, present work is focusing on
investigating $\text{Mn}_{0.5}\text{Cd}_{x}\text{Sr}_{0.5-x}\text{Fe}_2\text{O}_4$ nanocrystals, $(x = 0, 0.1, 0.2, 0.3, 0.4, 0.5)$, synthesized by the eco-friendly co-precipitation strategy and scrutinizing the impact of $\text{Cd}^{2+}$ cations replacement on their spectral, structural and ferrimagnetic features. The Nano-spinels were discriminated by XRD, FT-IR, HTEM and VSM strategies.

2. Experimental

Ultrafine $\text{Mn}_{0.5}\text{Cd}_{x}\text{Sr}_{0.5-x}\text{Fe}_2\text{O}_4$ nanocrystals, $(x = 0, 0.1, 0.2, 0.3, 0.4, 0.5)$, were synthesized by using the one-beaker and the cost-effective co-precipitation procedures [18] utilizing the equation:

$$0.5 \text{MnCl}_2.4\text{H}_2\text{O} + x \text{CdCl}_2.\text{H}_2\text{O} + (0.5-x) \text{SrCl}_2.6\text{H}_2\text{O} + 2 \text{FeCl}_3 + 8 \text{NaOH} \rightarrow \text{Mn}_{0.5}\text{Cd}_{x}\text{Sr}_{0.5-x}\text{Fe}_2\text{O}_4 + 8 \text{NaCl} + (9 - 5x) \text{H}_2\text{O} + 2 \text{O}_2$$

Exact proportions of the highly pure chlorides; manganese chloride, cobalt chloride, strontium chloride and ferric chloride were dispersed in distilled $\text{H}_2\text{O}$ under stirring. Thereafter, $\text{NaOH}$ acquis liquid was wisely dropped to the mixture under stirring till PH-value around 12. This mixture persistently heated up to nearly $80^\circ \text{C} / 2$ hours till co-precipitation reaction was accomplished. Afterwards, nano-precipitates were exposed to extensive washing strategy with distilled $\text{H}_2\text{O}$ to eliminate NaCl salts and unwanted remnants. Then, nano-precipitates dried at nearly $100^\circ \text{C}$, and ground to Nano-powders in agate mortar [18].

Nano-ferrites were discriminated by using GNR APD 2000 Pro X-ray diffractometer step-scan kind and CuKα1 radiations at wavelength $\lambda = 1.540598$ Å. Peak allocations and widths for prominent Supremes (311) for Nano-spinels were elicited using the expression; $a = d (h^2 + k^2 + l^2)^{1/2}$, whereas interior-planes distances $d$ were educed using Bragg's expression; $2 d \sin \theta = n \lambda$, $\theta$ is diffraction angle [18]. IR spectra for all Nano-spinels examined by utilizing Bruker-Tensor-27-FT-IR - type Spectrometer in the range 200 to $2000 \text{ cm}^{-1}$, at ambient temperature. Force constants $F_1$ and $F_2$ for A- and B-sites were elicited using the expression; $F = 4\pi^2C^2\nu^2\mu$, $C$ is light speed, $\nu$ is the vibrational mode allocation and $\mu$ is the reduced mass of vibrating atoms [19,20]. Magnetic hysteretic attitudes of Nano-samples have been scrutinized at ambient conditions using the vibrational Nano-samples magnetometer (LDJ) Electronic Inc. Troy, MI up to 25 kG. Furthermore, average nanoparticles sizes and morphologies have been picked up by the higher resolution transmissions electrons microscopy of the precise kind JEOL JEM – 2100 Electron Microscopes.

3, Results and discussion

3.1. X-ray diffractometric (XRD) testing

Nano-crystalline $\text{Mn}_{0.5}\text{Cd}_{x}\text{Sr}_{0.5-x}\text{Fe}_2\text{O}_4$ particles, $(x = 0, 0.1, 0.2, 0.3, 0.4, 0.5)$, verified the complete emersion of the Nano-spinel single-phase which was precisely illuminated in XRD plots in figure 1.

![Figure 1](image1.png)

**Figure 1** XRD plots of as-fabricated Nano-spinels $\text{Mn}_{0.5}\text{Cd}_{x}\text{Sr}_{0.5-x}\text{Fe}_2\text{O}_4$, $(x = 0, 0.1, 0.2, 0.3, 0.4, 0.5)$. 


Essentially, protruded Supremes in XRD plots belong to one-phase spinel configuration in all the nanocrystals which was verified by matching with JCPDS cards (JCPDS card no. 00-001-1111 and 00-010-0319). Obviously, for the ultrafine nano-size feature of these Nano-spinels thus appears relatively broader XRD peaks in figure 1, as further emphasized with their fine crystallite sizes for all nanoparticles as indicated in table 1. Lattice constant a showed nonlinear trend with x (table 1), which is imputed to the Cd$^{2+}$ cations (1.09 Å) replacement instead of the voluminous Sr$^{2+}$ cations (1.32 Å) within A-sites [21]. Cd$^{2+}$ cationic addition instead of Sr$^{2+}$ cations induces crystalline anisotropy which is assigning to the larger mismatch between Cd$^{2+}$ and Sr$^{2+}$ cationic radius [21]. The increase in lattice parameter with larger Cd$^{2+}$ cationic addition is imputed to the formation of ferromagnetically ordered nanoclusters within the Nano-spinels [22].

3.2. Structural Phase Analysis

Unit cell volumes for these Nano-spinels have been elicited using the expression [23]; $V_{cell} = a^3$. The unit cell volume V revealed a similar demeanor to that of the lattice constant a, (table 1). V demeanor with increase in Cd$^{2+}$ cationic ratio $x$, due to the replacement process instead of Sr$^{2+}$ cations and the synchronous variations in the crystalline anisotropy [21].

X-ray densities were finely elicited from the expression [24]:

$$D_x = \frac{ZM}{N_A V}$$

where molecular number / unit cell is ($Z = 8$); molecule weight is $M$ and Avogadro number is $N_A$. $D_x$ revealed nonlinear behavior with $x$, which is imputed to the replacement process of the lighter atomic weight Sr$^{2+}$ (87.62) by the much heavier Cd$^{2+}$ (112.41) as well as immigration of cations between sub-lattices.

Dislocations density $\delta$ was well educed by using [25]:

$$\delta = \frac{1}{R^2}; R \text{ is the crystallite size.}$$

Distortions factor $g$ was elicited using the expression [25]:

$$g = \frac{\beta_{\lambda/2}}{\tan \theta}$$

Table 1 displays the reliance of $g$ and $\delta$ on $x$, where both $g$ and $\delta$ depend on the alterations in lattice-spacing and O anionic concentration in Nano-samples [25]. It is displayed that $g$ and $\delta$ gradually rise with $x$. This may be imputed to both the atomic disturbances as well as the decline of the lattice strain $\varepsilon$ with $x$ [25]. Specified surface area $S$ of nanoparticles was elicited utilizing the expression [26]:

$$S = \frac{6000}{R_{XRD}D_x}$$

Lattice strain $\varepsilon$ was concluded utilizing the formula [26]:

$$\beta_{\lambda/2} \cos \theta = \frac{0.94\lambda}{R_{XRD}} + 4\varepsilon \sin \theta$$

The strain $\varepsilon$ within these nanocrystals declines with Cd$^{2+}$ cationic addition, (table 1), assigning to the induced crystalline anisotropy [21]. Whereas, the specific surface area $S$ has revealed a surging trend with $x$, (figure 2). As a consequence, doping of Cd$^{2+}$ cations gives significance to decline in crystallite sizes $R$ values in-between 32.1 –and– 16.05 nm, (figure 2).
Figure 2. Demeanors of the crystallite sizes $R \text{ (nm)}$ and the specific surface area $S \text{ (m}^2/\text{g)}$ versus $\text{Cd}^{2+}$ cationic content $x$.

Table 1. Lattice parameter $a$, strain $\varepsilon$, unit cell volume $V$, the X-ray density $D_x$, distortion parameter $g$ and dislocation density $\delta$ of the as-prepared spinel $\text{Mn}_{0.5}\text{Cd}_{x}\text{Sr}_{0.5-x}\text{Fe}_2\text{O}_4$ nanocrystals, $(x = 0, 0.1, 0.2, 0.3, 0.4, 0.5)$, error $= \pm 0.02$.

| $x$ | $a$ (Å) | $\varepsilon$ | $V$ (Å$^3$) | $D_x$ (gm.cm$^{-3}$) | $g$ (nm$^{-2}$) | $\delta$ (nm$^{-2}$) | $Z$ (nm) |
|-----|--------|--------------|-------------|-----------------|-------------|-----------------|---------|
| 0   | 8.451  | -0.032       | 603.447     | 5.435           | 0.0142      | 0.00097         | 35      |
| 0.1 | 8.432  | -0.041       | 599.554     | 5.526           | 0.0179      | 0.00156         | 28.3    |
| 0.2 | 8.491  | -0.046       | 611.938     | 5.468           | 0.0205      | 0.00197         | 25.6    |
| 0.3 | 8.422  | -0.051       | 597.345     | 5.657           | 0.0225      | 0.00242         | 22.8    |
| 0.4 | 8.484  | -0.055       | 610.697     | 5.587           | 0.0245      | 0.00279         | 21.6    |
| 0.5 | 8.483  | -0.065       | 610.538     | 5.643           | 0.0288      | 0.00389         | 20      |

3.3. Fourier Transform Infrared (FT-IR) spectral Plots

FT-IR spectral plots of $\text{Mn}_{0.5}\text{Cd}_{x}\text{Sr}_{0.5-x}\text{Fe}_2\text{O}_4$ nanocrystals, $(x = 0, 0.1, 0.2, 0.3, 0.4, 0.5)$, are illustrated in figure 3. Six absorption Supremes; $v_1$, $v_2$, $v_3$, $v_4$, $v_5$, and $v_T$ were protruded in the FT-IR spectral plots (table 2). Distinctive allocations of spinels $v_1$ and $v_2$ were emerged in IR spectral chart for all these Nano-spinels. $v_1$ was observed in the range of 565.11 – 586.35 cm$^{-1}$ and $v_2$ in-between 397.32 – 445.56 cm$^{-1}$. $v_1$ corresponds for the stretching vibrational allocations of $\text{Fe}^{3+}$- $\text{O}^2-$ bond among A-sites possessing topmost restoring forces and $v_2$ to bond-bending vibrational allocations of $\text{Fe}^{3+}$- $\text{O}^2-$ bond among the octahedral B-sites [20,21,27]. The two emerging bands around 445 and 580 cm$^{-1}$ are imputing to the cation–anion interactions in B- and A-sites, in order [27]. Vibrations normal modes of A-site clusters are exceeding over that of B-site clusters imputing to the shortest bonding lengths of A-site clustering status. This is imputed to the stronger covalent bonding of $\text{Fe}^{3+}$ cations existing in A-sites compared with B-sites [20,21,27]. $v_1$ and $v_2$ are shifted to lower energies which impute to cationic motion in-between sublattices.
parallel with substitution process with Cd\textsuperscript{2+} cations which leads to varying the bond lengths. \(\nu_4\) was emerged in the range of 246.82 – 241.09 cm\(^{-1}\) corresponding to the lattice vibrational status of the system. It relies on masses of A-site divalent cations including their complexes, Fe\textsuperscript{2+}–O\textsuperscript{2-}, Mn\textsuperscript{2+}–O\textsuperscript{2-}, Cd\textsuperscript{2+}–O\textsuperscript{2-} and/or Sr\textsuperscript{2+}–O\textsuperscript{2-} [20,21,27]. Triplet allocations \(\nu_T\) observed at around 1620 cm\(^{-1}\) corresponds to the retaining H\textsubscript{2}O (humidity) in these Nano-spinels during the preparation process. The band \(\nu_A\) emphasizes the presence of divalent cations Fe\textsuperscript{2+}, Sr\textsuperscript{2+}, Cd\textsuperscript{2+} and/or Mn\textsuperscript{2+} amongst A-site, whereas \(\nu_B\) is assigning to Fe\textsuperscript{4+}–O\textsuperscript{2-} and/or Mn\textsuperscript{4+}–O\textsuperscript{2-} complexes [22]. Fe\textsuperscript{4+} and Mn\textsuperscript{4+} cations emerge due to the electronic jumping in-between the Mn\textsuperscript{2+} and Fe\textsuperscript{3+} cations [20,21,22,27]. Fig. 4 clarifies the reliance of \(F_1\) and \(F_2\) force cont.’s of the A- and B-sites, orderly, on Cd\textsuperscript{2+} cations content \(x\). It is eminent that \(F_1\) and \(F_2\) decline with \(x\), these variations are imputed to the changing of bond lengths, porosity and the Cd\textsuperscript{2+} cations replacement process [20,21,27].

The deduced Debye temperature \(\Theta_D\) was derived from the expression [28,29]:

\[
\Theta_D = \frac{\hbar c \nu_{av}}{k} = 1.438\nu_{av} \quad \text{and} \quad \nu_{AV} = \frac{\nu_1 + \nu_2}{2} \quad \text{for cubic Nano-spinel;}
\]

Wave numbers average value is \(\nu_{av}\), \(\hbar = h/2\pi\), \(h\) is the Plank const., Boltzmann's const. is \(k\), \(\hbar C / k\) value for Nano-spinels is 1.438, \(\Theta_D\) reliance on \(x\) is plotted in Fig. 4. It is explicit that, \(\Theta_D\) rises versus Cd\textsuperscript{2+} cations content \(x\) surge. \(\Theta_D\) variations essentially rely on the specified heat energy theorem, supporting that conducting electrons (n-type carriers) could absorb portion of thermal energy declining \(\Theta_D\) [28,29]. \(\Theta_D\) surge with \(x\) is assigning to the decline of conducting electrons numbers \(N_e\) (n-type) in synchrony with the rise of conducting holes numbers \(N_h\) (p-type). Threshold frequencies \(\nu_{th}\) are distinguishing of the electronic transitions within Nano-spinels, precisely contrived from uppermost spots of FT-IR plots [20]. Regarding electronic transitions surge, thus the threshold frequency \(\nu_{th}\) also surges with \(x\), (table 2) [20].

Threshold energy \(E_{Th}\) was educed using the expression [20]:

\[
E_{Th}(eV) = \hbar C \nu_{Th} ;
\]

Planck’s constant is \(h\), light velocity is \(C\) and threshold frequency is \(\nu_{Th}\). It is seen that, \(E_{Th}\) also surges with Cd\textsuperscript{2+} cationic ratio increase \(x\) and this is imputed to the essential dependence of \(E_{Th}\) on \(\nu_{Th}\), hence both are rising with \(x\), (table2).

![Figure 3. FT-IR plots of as-prepared spinel Mn\textsubscript{0.5}Cd\textsubscript{0.5}Sr\textsubscript{0.5}Fe\textsubscript{2}O\textsubscript{4} particles, \((x = 0, 0.1, 0.2, 0.3, 0.4, 0.5)\).](image-url)
Table 2. FT-IR absorbing/vibrating allocations $\nu_n$, $n = 1, 2, \ldots, B$, Threshold energy $E_{\text{Th}}$ (eV), for the as-prepared spinel Mn$_{0.5}$Cd$_x$Sr$_{0.5-x}$Fe$_2$O$_4$ nanoparticles, ($x = 0, 0.1, 0.2, 0.3, 0.4, 0.5$), error $= \pm 0.02$.

| $x$ | $\nu_1$ (cm$^{-1}$) | $\nu_2$ (cm$^{-1}$) | $\nu_4$ (cm$^{-1}$) | $\nu_A$ (cm$^{-1}$) | $\nu_B$ (cm$^{-1}$) | $\nu_T$ (cm$^{-1}$) | $E_{\text{Th}}$ (eV) |
|-----|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 0   | 586.35           | 445.56           | 246.82           | 842.86           | 1010.65          | 1612.45          | 0.0951           |
| 0.1 | 580.56           | 437.83           | 244.95           | 844.79           | 1031.89          | 1614.38          | 0.0959           |
| 0.2 | 576.71           | 428.19           | 244.95           | 846.73           | 1035.75          | 1616.31          | 0.0961           |
| 0.3 | 574.77           | 420.47           | 243.03           | 848.66           | 1041.53          | 1618.22          | 0.0963           |
| 0.4 | 568.99           | 397.32           | 243.01           | 850.58           | 1047.34          | 1620.14          | 0.0967           |
| 0.5 | 565.11           | 435.91           | 241.09           | 854.45           | 1058.89          | 1622.06          | 0.0976           |

Figure 4. Variating features of $F_1$ and $F_2$ force cons, threshold frequency $\nu_{\text{Th}}$ and Debye temperature $\Theta_D$ with Cd$^{2+}$ cationic content $x$. 
3.4. Ferrimagnetic Hysteretic plots

RT Ferrimagnetic hysteretic plots of the as-fabricated Nano-crystalline Mn_{0.5}Cd_{x}Sr_{0.5-x}Fe_{2}O_{4} particles, (x = 0, 0.1, 0.2, 0.3, 0.4, 0.5) are illustrated in figure 5. Nanocrystals magnetization emerges from the precise role of super-exchanging interactions, move of domain borderlines, spin rotation and precession. Obviously, the hysteresis loops possess relatively narrow hysteretic attribute disclosing the soft ferrimagnetic features for these Nano-spinels. The well-concluded saturated magnetization Ms and coercive field Hc trends with Cd^{2+} cations ratio x are registered in table 3. Explicitly, Ms declines linearly versus x, whilst Hc rises nonlinearly. Trends of Ms and Hc impute to nano-size nature of the crystallite size, cationic disturbances and emigrations within various crystallite positions and changing of spin canting. Declining of Ms impute to alleviation of B-allocations magnetization by permutation of nonmagnetic Cd^{2+} cations replacing nonmagnetic Sr^{2+} cations within A-site, which causes cationic disturbances and emigrations within the crystalline sites, which in turn influence the nanocrystalline anisotropy as well, affecting both Ms and Hc [18,21,30,31]. This promotes the diminishing of super-exchanging magnetic interactions rates amongst nanocrystal sub-lattices by changing numbers of magnetic bonds; \( Fe_{A}^{3+} - O - Fe_{B}^{3+} \), i.e. diminishing A-B ferri-magnetic interactions (M_{A-B}), hence Ms declines. Declining of Ms (table 3), may be imputed to spin canting clutter within nanoparticles superficies stratum as well as local chemical disorders at the surface [18,21,30,31].

Coercivity Hc lie in the range of 186.65 – 312.16 G giving rising behavior with Cd^{2+} ionic ratio x, which refer to surge of localizing distortions in interior of grain district. Atomic chemical disturbances on grain borderlines hinder their domain walls motion leading to surge of Hc and decline of Ms. Elicited residual magnetization Mr is presented in table 3. Evidently, elicited Mr estimation is relatively small reflexing ferri-magnetic behavior of nanocrystals. Slight rising of Mr was imputed to spin canting disordering and super-exchanging interactions variation. This slight rise may refer to possessing of appointed nanocrystals their magnetizing status and conducting as magnetic materials explaining the net magnetization of the nano-sample. Table 3 illuminates the variation of the squareness Mr/Ms with Cd^{3+} cationic ratio x. Explicitly, Mr/Ms rises nonlinearly with x imputing to decline of Ms and rise of Hc [18,21,30,31]. The anisotropy constant K was elicited using the expression [18,21];

\[
Hc = 0.96K / Ms
\]

It is explicit that, the coercivity, surface effects and superficies spinning impact magnetization and anisotropic energy. Also, anisotropic cons K is influenced by many factors like; Ms, R, spin canting, magneto-crystalline, constitute and superficies anisotropies [18, 21, 30, 31]. Variation of the exchange interactions by cationic disorderliness through permutation procures declining of anisotropic energy and as a consequence K, as indicated in table 3.

The magnetic moment n_{B} was elicited using [21,31];

\[
n_{B} = \frac{M \times Ms}{5585}
\]

Table 3 shows that n_{B} declines with x which is due to the spin canting and decline in A–B super-exchanging magnetic interactions.
Fig. 5 Ferri-magnetic hysteretic plots of as-fabricated spinel Mn$_{0.5}$Cd$_x$Sr$_{0.5-x}$Fe$_2$O$_4$ particles, ($x$ = 0, 0.1, 0.2, 0.3, 0.4, 0.5).

Table 3. The coercive field $H_c$, the saturated magnetization $M_s$, the residual magnetization $M_r$, the squareness $M_r/M_s$, the magnetic moment $n_B$, and the anisotropy cons $K$ for the as-fabricated spinel Mn$_{0.5}$Cd$_x$Sr$_{0.5-x}$Fe$_2$O$_4$ nanocrystals, ($x$ = 0, 0.1, 0.2, 0.3, 0.4, 0.5), error = ± 0.02.

| $x$ | $M_s$ (emu/g) | $H_c$ (G) | $M_r$ (emu/g) | $M_r/M_s$ | $n_B$ ($μ_B$) | $K$ (erg/Gauss) |
|-----|---------------|-----------|---------------|-----------|---------------|----------------|
| 0   | 30.12         | 201.23    | 4.98          | 0.165     | 1.332         | 6313.59        |
| 0.1 | 26.32         | 194.14    | 3.61          | 0.138     | 1.176         | 5322.67        |
| 0.2 | 23.98         | 189.68    | 3.14          | 0.132     | 1.082         | 4738.05        |
| 0.3 | 22.65         | 186.65    | 2.92          | 0.129     | 1.032         | 4403.76        |
| 0.4 | 20.45         | 259.85    | 5.66          | 0.276     | 0.941         | 5535.35        |
| 0.5 | 16.05         | 312.16    | 5.19          | 0.325     | 0.745         | 5218.93        |

3.5. High resolution transmitting electronic microscopy (HTEM)
HTEM pictures of as-fabricated Nano-crystalline Mn$_{0.5}$Cd$_x$Sr$_{0.5-x}$Fe$_2$O$_4$ particles, ($x$ = 0, 0.1, 0.2, 0.3, 0.4, 0.5) are manifested in figure 6. HTEM pictures exhibiting that nanoparticles were aggregated which may be imputed to their obvious magnetic moments. Nanoparticles sizes $Z$ lie in the range from 20 to 35 nm as illuminated in table 1. Variation of $Z$ with $x$ is close to R, whereas $Z$ estimations are lightly rising which may be referred to small amorphous stratum on nanoparticle’s surfaces. That is because XRD
detects only the crystalline portions interior nanoparticle, whilst HTEM gives overall picturing of nanoparticle [18,31].

Figure 6. HTEM pictures of as-prepared spinel Mn_{0.5}Cd_{x}Sr_{0.5-x}Fe_{2}O_{4} particles, (x = 0, 0.1, 0.2, 0.3, 0.4, 0.5).

4. Conclusion
As-prepared Nano-crystalline Mn_{0.5}Cd_{x}Sr_{0.5-x}Fe_{2}O_{4}, (x = 0, 0.1, 0.2, 0.3, 0.4, 0.5) were synthesized by the one-beaker and the cost-effective co-precipitated strategy, and scrutinized utilizing XRD, FT-IR spectra, VSM and HTEM. XRD investigation revealed the evolution of the spinel single-phase for all these nano-spinels. Crystallite size R values ranged from 16.05 to 32.1 nm, with declining behavior with x. The (ν₁, ν₂, ν₄, ν₅, ν₆ and ν₇) six bands appearing in FT-IR spectral plots were interpreted according to their bonds and sites. Elicited operators rely on Cd^{2+} cations permutation operation instead of Sr^{2+} cations. Magnetic merits proved the soft-magnetic features for all these nanocrystals, whereas, all the magnetic parameters were influenced by the replacement process with Cd^{2+} cations. HTEM images exhibited aggregations for the nanoparticles, where average particles sizes Z ranged from 20 to 35 nm and were lightly rising over crystallite sizes R.

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