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Binary synthesis ZnSe on a glassy carbon electrode in a choline chloride-urea (ChCl-U) medium

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- ✓ *binary*

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Abstract: The electrodeposition of the binary ZnSe was studied on a glassy carbon electrode in a choline chloride-urea (ChCl-U) medium at 100°C. The results obtained by cyclic voltammetry of the mixture of selenium and zinc present a new peak that would be linked to the formation of the binary whose dissolution allows to observe the peak linked to the oxidation of zinc but mainly the presence of the oxidation of Se (0) precursor. The speed and time allow an accumulation of the deposit of the binary ZnSe reflecting a slow deposition kinetics controlled by diffusion. The chronoamperometric analysis confirms the synthesis of ZnSe following a three-dimensional (3D) nucleation and growth of the progressive type. The SEM analysis allows to observe the presence of a thin layer that would be linked to the deposition of the binary ZnSe, a result that is confirmed by the UV-visible analysis through the presence of an absorption peak at 264 nm. A bibliometric analysis gathered on Scopus using "deep eutectic solvents" was conducted from 2004 to 2025. China is the prolific country followed by India.

1. Introduction

The ever-increasing need for electricity and the depletion of raw materials used to produce it are driving industries toward the production of photovoltaic (PV) modules mainly based on thin films. However, PV thin films are semiconductors, some of which are formed from transition metal chalcogenides (CdSe, CdTe, MnCe, ZnSe and ZnS) (Romeo and Artegiani, 2021; Faremi *et al.*, 2022; Elafia *et al.*, 2023). Due to its non-toxicity and abundance of elements, ZnSe has attracted considerable interest in several fields. Its band gap (2,7eV) is located in the optimal absorption region of the solar spectrum, coupled with its physicochemical properties, has led to its use in the fields of PV and electronics (Ramasamy *et al.*, 2011). Methods such as chemical vapor deposition (Metin *et al.*, 2011; Hankare *et al.*, 2008), sol-gel deposition (Li *et al.*, 1994; Hao *et al.*, 2007), vacuum physical vapor deposition (Wei *et al.*, 1992; Sanchez *et al.*, 2000), and electrodeposition (Natarajan *et al.*, 1994), (Chandramohan *et al.*,1997; Samantilleke *et al.*, 1998), have been used for thin film production. Among the different methods, electrodeposition is relatively simple to implement, less expensive in terms of energy savings, raw material and equipment. In addition, this technique is suitable for large and irregular surfaces (Yushanjiang *et al.*, 2014; Krishnam *et al.*,1992; Fernandez *et al.*, 2003; Mann *et al.*,

2009; Bienkowski *et al.*,2010). There is very good documentation in the literature on the electrodeposition of ZnSe in different media, including aqueous (Metin *et al.*, 2011; Hankare *et al.*, 2008; Riveros *et al.*, 2003; Bouroushian *et al.*,2006), organic (Kumar *et al.*,2012) and high-temperature molten salts (Wei *et al.*, 1992; Natarajan *et al.*, 1994; Chandramohan *et al.*,1997; Sanchez *et al.*, 2000). However, the impact of these media on the environment is significant and it is necessary to find an alternative to these so-called conventional, environmentally unfriendly media. In this sense, for several years, we have witnessed the emergence of unconventional media, including deep eutectic solvents (DETs). Deep eutectic solvents are used because of their easy preparation. They are relatively biodegradable with an attractive cost and a low ecological footprint (Choi *et al.*,2011). These media were introduced in 2003 by Abbott and al. (Abbott *et al.*, 2003), with the choline chloride-urea mixture in a stoichiometric ratio of 1:2. In 2014, Smith and al (Smith *et al.*, 2014), generalized DETs as systems formed from a eutectic mixture of Lewis or Bronsted acids and bases. Thus, since then, several authors have used deep eutectic solvents for the electrodeposition of metals such as silver (Rayée *et al.*, 2017; Sebastián *et al.*, 2013; Sebastián *et al.*, 2016), copper (Sebastián *et al.*, 2015; Obeten *et al.*, 2017; Bernasconi *et al.*, 2015), zinc (Moutari *et al.*, 2023; Yang *et al.*, 2014; Xueliang *et al.*, 2016: Harati *et al.*, 2012; Bucko *et al.*, 2019; Vieira *et al.*, 2015; Abbott *et al.*, 2011), selenium (Cojocaru *et al.*, 2016; Bougouma *et al.*, 2012), manganese (Moutari *et al.*, 2025; Bozzini *et al.*, 2012; Guo *et al.*, 2020), etc. However, very few studies concern the electrodeposition of binary ZnSe in DETs medium. One of the rare studies on the ZnSe system encountered is that carried out by Bougouma and al. (Bougouma *et al.*, 2014) in ChCl-U medium on a gold electrode. According to these authors, it is possible to form ZnSe in ChCl-U medium in the presence of the precursor salts Zn and Se. The cathodic redissolution study allowed the latter to highlight the presence of two anodic peaks corresponding to the presence of Zn (II) and Se (0) from the formed binary.

This work consists of the electrodeposition of the ZnSe binary on a glassy carbon electrode, in a choline chloride-urea medium. The techniques used are cyclic voltammetry, chronoamperometry, UV-visible, and SEM. This article is a continuation of the article on the electrodeposition of zinc in a ChCl-U medium on a glassy carbon electrode (Moutari *et al.*, 2023). The optimal zinc deposition temperature is 100°C. This temperature is used for the deposition of the binary in ChCl-U medium.

2. Materials and experimental methods

2.1. Reagents and solution preparation

To study the electrochemical behavior of the ZnSe binary, two reagents were used for the preparation of the ChCl-U solvent. Choline chloride (ChCl) (Alfa Aesar, 98%), purified by recrystallization from absolute ethanol (VWR Chemicals NORMAPUR), filtered and dried under vacuum and urea (VWR Chemicals NORMAPUR) all mixed in a molar ratio of 1:2. The precursors SeO_2 (Alfa Aesar, 99.4%) and $ZnSO_4.7H_2O$ (VWR Chemicals NORMAPUR, 99.99%) were weighed and added directly without prior treatment.

The entire solid mixture was heated at 100°C for 2 hours under magnetic stirring, in an oil bath, using a hot plate (IKA C-MAGHS7) equipped with a temperature sensor and a temperature control device (IKATRO NETS-D5), until a homogenous and transparent liquid was obtained.

2.2. Experimental methods

The electrochemical experiments were performed using a three-electrode system connected to an Autolab PGSTAT302N potentiostat (Metrohm). Before use, all glassware was cleaned with Milli-Q water and dried in an oven. The working electrode was made of glassy carbon (BASI, geometric

surface=0.0707 cm^2). It was polished with an alumina (1.0 µm)-water suspension on a porous neoprene mat (Struers), then subjected to two 5-minute ultrasonic waves and rinsed with Milli-Q water to remove all traces of alumina, then dried with nitrogen. The counter electrode was a platinum grid with a surface area of approximately 3 cm^2. It was flame –cleaned using a blowtorch using an incandescent flame. A silver wire insulated in a capillary tube containing the electrolyte consisting of a mixture of choline chloride and urea in a molar ratio of 1:2 was used as the reference electrode. It was rinsed with water and dried using absorbent paper.

3. Results and Discussion

3.1. Bibliometric Analysis.

The bibliometric analyses involve gathering data from scientific databases and utilizing techniques such as co-occurrence network analysis mapping, citation analysis, and exploring the relationship between key topics and their impact on the field of study (N'diaye *et al.*, 2022; Bazzi *et al.*, 2023; Moutari *et al.*, 2023; Hammouti *et al.*, 2025; Kadda *et al.*, 2025). The time periods in 2004–2025 research on "deep eutectic solvents" has evolved thematically, leading to a comprehensive examination, enhanced understanding, the evolution of the production and the collaboration between institutions and countries. The net progress in articles started over 2010 to more than 3000 articles both in 2024 and 2025 as shown in **Figure 1**. Analysis of the **Figure 2** left reveals that more than 98% are article, reviews, book chapters and conference papers, and **Figure 2** right over 53% of the contribution concerns the chemistry and Chemical engineering, Materials sciences and Engineering. The others are distributed across applications such as physics, energy, agriculture, biochemistry… The most prolific authors interesting by this domain are list in **Figure 3.** Hachim and Afshar Mogaddam are the top slightly less than 100 papers. China is widely the highest country investing and contributing in the domain exceeding 6600 articles as indicated in **Figure 4**. The publication of articles needs the choice of the higher impact journals, such as the International Journal of Biological Macromolecules (IF 8.5 and 10.3 CiteScore) selected as the first journal of the list containing 5 journals (**Figure 5**). The second one is Microchemical Journal (IF 5.1 and 6.2 CiteScore).

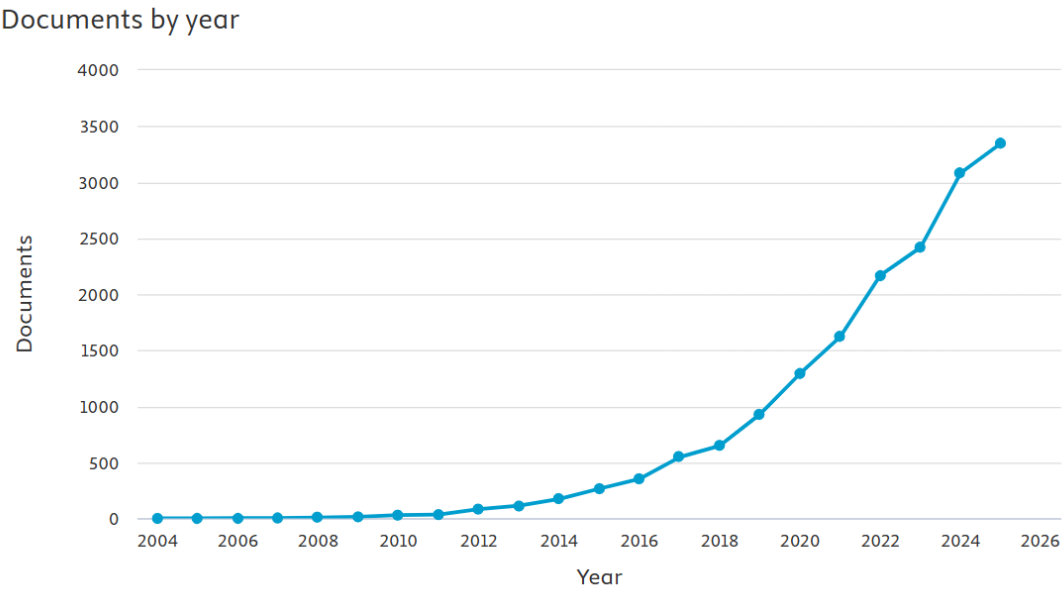

Figure 1. Evolution of the production from 2004 to 2025

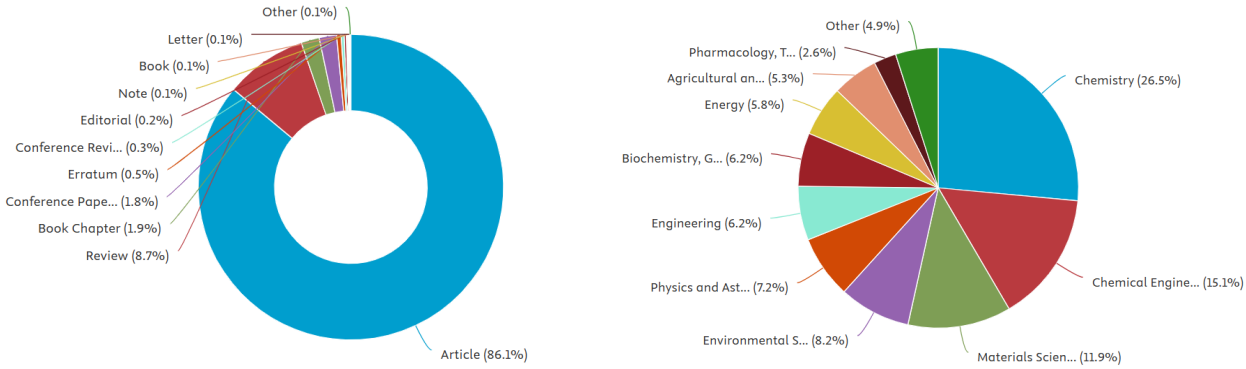

Figure 2. Repartition of the production: left: type of papers and right: by topics

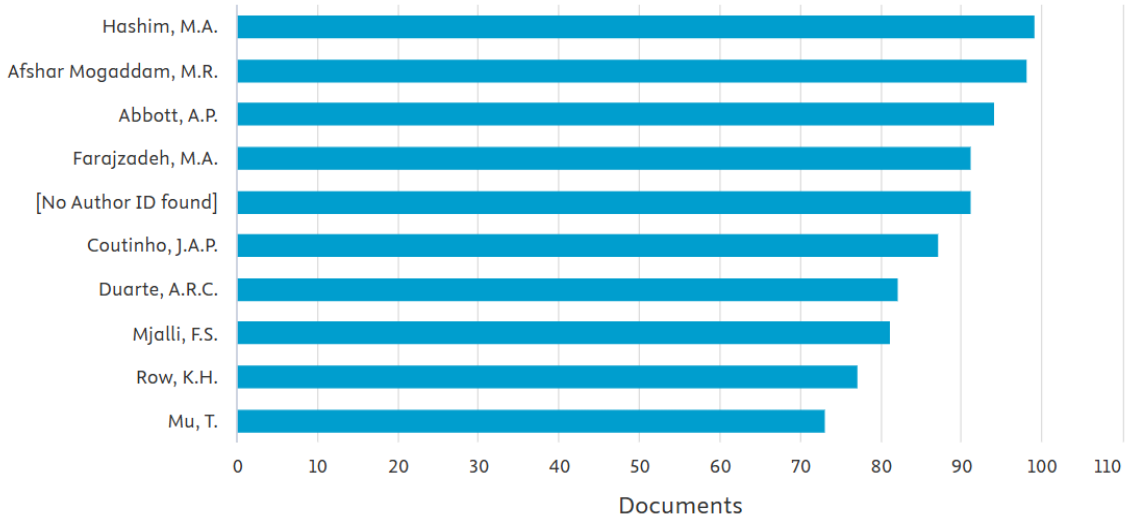

Figure 3. Most ten published authors

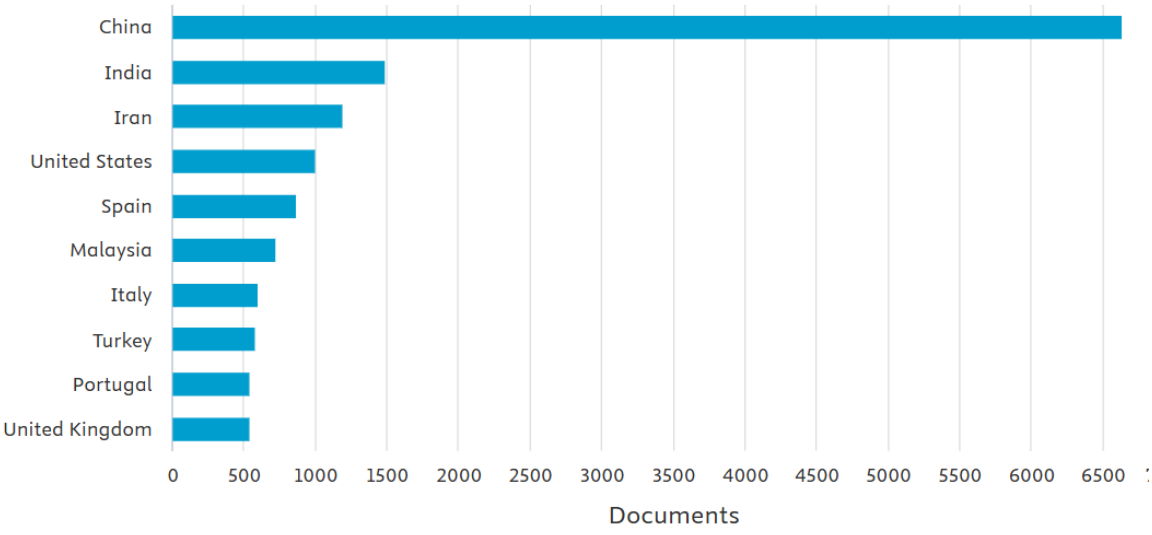

Figure 4. Most ten published countries

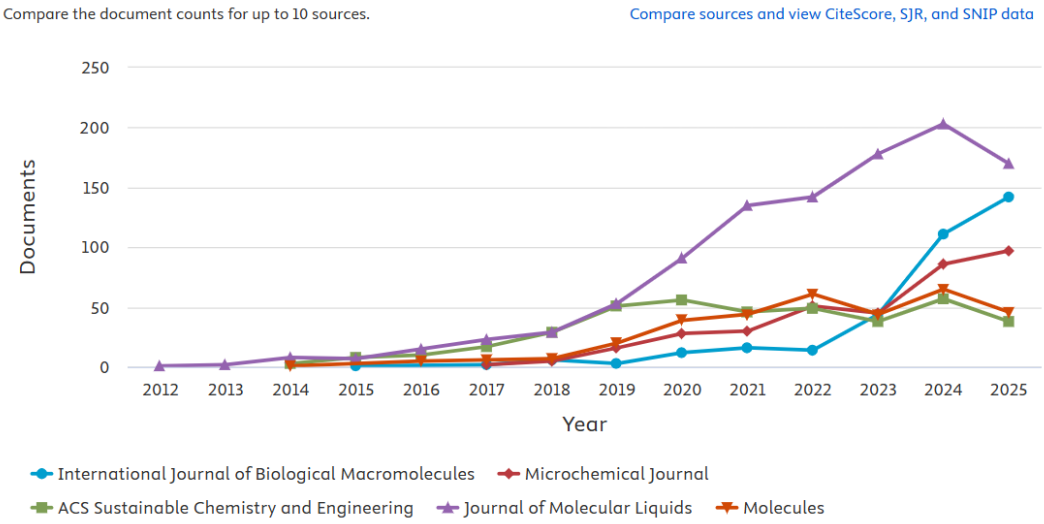

Figure 5. Best Journals used by Authors

3.1. Potentiodynamic study of the electrochemical behavior of binary ZnSe on a glassy carbon electrode (GCE).

For clarity, the study begins by recording the cyclic voltammograms of the two precursor salts, presented separately. The cyclic voltammogram recorded in a ChCl-U medium + 10 mmol of SeO_2 is shown in **Figure 5**. Analysis of the figure reveals two cathode peaks named C1 and C2 at potentials of -0.4 V and -0.8 V, corresponding respectively to the transition from Se(IV) to Se (0) and Se (0) to Se (-II) according to equations (1) and (2):

C_1: $Se(IV) + 4e^- \rightarrow Se(0)$ (1)

C_2: $Se(0) + 2e^- \rightarrow Se(-II)$ (2)

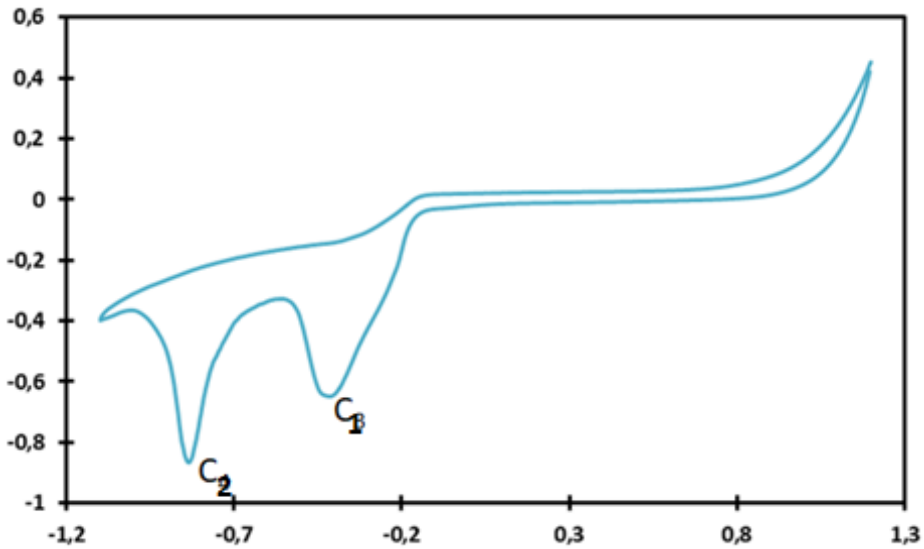

Figure 5: Cyclic voltammogram of the ChCl-U + 10 mmol of SeO_2 system, on a glassy carbon electrode, v=10 $mV.s^{-1}$, at T=100°C.

Figure 6 shows the cyclic voltammogram recorded on a glassy carbon electrode (GCE) in ChCl-U+50 mmolal $ZnSO_4.7H_2O$ medium. The recorded voltammogram shows a cathodic peak C3 at a potential

of -1.18 V and an anodic peak A1 at a potential of +0.90 V, corresponding respectively to the transition from Zn(II) to Zn(0) according to equation (3) and the anodic response A1 corresponds to the reverse process according to equation (4)

C_3: $Zn(II) + 2e^- \rightarrow Zn(0)$ (3)

A_1: $Zn(0) \rightarrow Zn(II) + 2e^-$ (4)

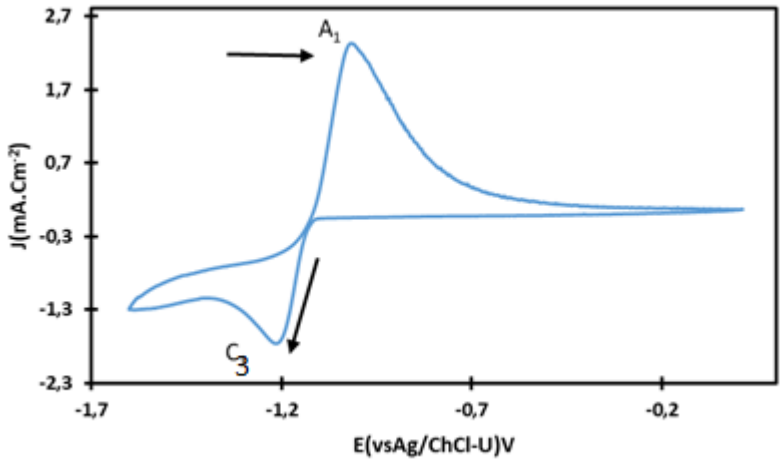

Figure 6: Cyclic voltammogram of the ChCl-U + 50 mmol of $ZnSO_4.7H_2O$ system, on a glassy carbon electrode, v=10 $mV.s^{-1}$, at T=100°C

The system formed by the mixture of precursor salts (50 mmol of $ZnSO_4.7H_2O$ and 10 mmol of SeO_2) in ChCl-U medium allows the recording of the cyclic voltammograms presented in **Figure 7**. These recorded voltammograms correspond to the study of the interdependence of the peaks which allows the highlighting of the peak corresponding to the formation of the binary ZnSe. Thus at the potential of -1.2V, we observe a cathodic peak C1 and an anodic peak A1 corresponding respectively to the reduction of Se (IV) to Se (0) and the oxidation of Zn (0) to Zn (II). When the inversion potential is between -1.3V and -1.6 V, all the voltammograms present the cathodic peaks C1 and C4 and the anodic peaks A1 and A2. The deposition of C4 leads to an increase in the peak A1 and the appearance causes the disappearance of peaks corresponding to the deposition of Zn (0) and Se (0), which would be linked to the synthesis of ZnSe (Mirtat *et al.*, 2002), according to equation (5)

$$Zn(II) + 2e^- + Se(0) \rightarrow ZnSe \quad (5)$$

At a potential more negative than -1.2 V, the appearance of a second peak A2, is observed on the anodic side, along with a progressive increase in the density of both peaks. Beyond the potential of -1.4 V, the intensity of peak A1 decreases inversely to that of peak A2. Everything suggests that the potential of -1.4 V would be the optimal for the formation of the ZnSe binary.

The inverse variations in the intensities of the anodic peaks linked respectively to the formation of the binary compound and to selenium could suggest that, depending on the potential, the formation of the binary compound is accompanied by a phase more or less rich in selenium. The free enthalpy of formation of the binary ZnSe ($\Delta G°f$=-154,4kJ) is negative, meaning that the compound formed is thermodynamically stable compared to its constituent elements in their standard state. This result is of the same order as that obtained by (Kroger *et al.*, 1978).

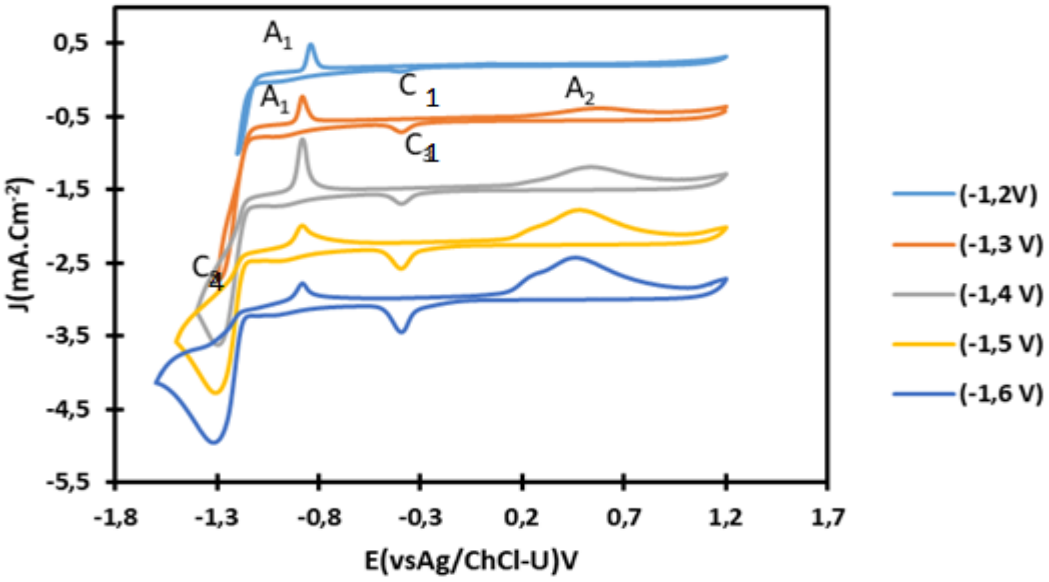

Figure 7: Cyclic voltammograms of the ChCl-U +10 mmol of SeO_2 + 50 mmol of $ZnSO_4.7H_2O$ system, at different cathode terminals, on a glassy carbon electrode, v=10 $mV.s^{-1}$, at T=100°C.

Figure 8 shows cyclic voltammograms of the binary system recorded at different scan rates in the potential window from + 1.2 V to -1.4 V. An increase in the speed leads to an increase in the intensity of the cathode peak C4 and that of the anodic peaks A1 and A2. This electrochemical phenomenon shows a linear trend, suggesting a process typical of diffusion-controlled reaction kinetics.

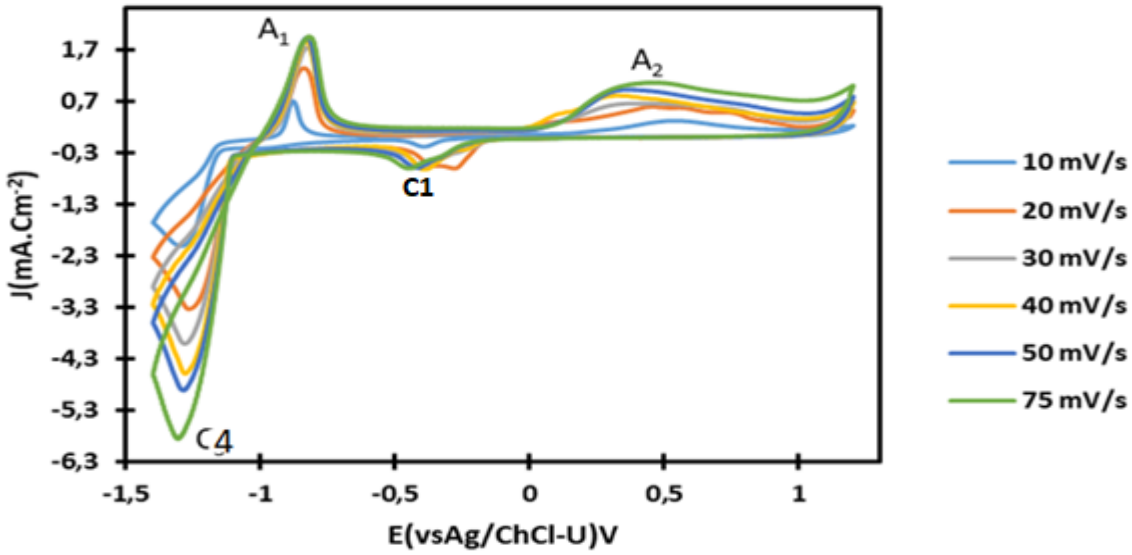

Figure 8: Cyclic voltammograms of the ChCl-U +10 mmol of SeO_2 + 50 mmol of $ZnSO_4.7H_2O$ system, on a glassy carbon electrode, at different scan rates, T=100°C.

Linear sweep voltammograms from the deposition potential of -1.4 V to positive potentials are shown in **Figure 9**. Two anodic peaks A1 and A2 are clearly observed during the different experiments corresponding to the dissolution of the ZnSe binary deposit. The increase in the current density of peaks A1 and A2 with time indicates an accumulation of material on the electrode surface related to the formation of a ZnSe deposit. However, the density growth of peak A2 appears to be greater than that of peak A1. This result suggests a greater presence of selenium in the formation of the ZnSe binary. In

this case, the binary could be a non-stoichiometric compound, or the formation of the binary could be accompanied by deposition of Se.

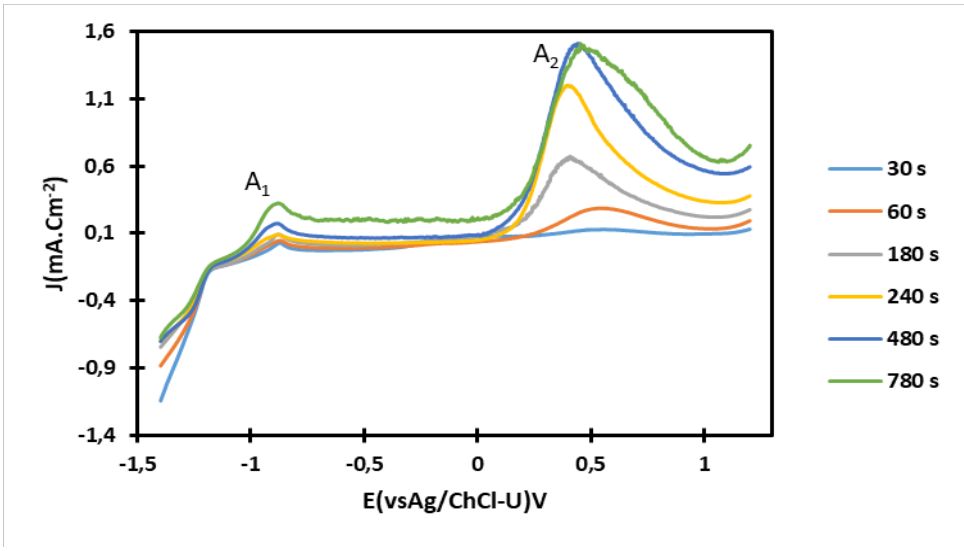

Figure 9 : Linear voltammograms of the ChCl-U +10 mmol of SeO_2 + 50 mmol of $ZnSO_4.7H_2O$ system, recorded on a glassy carbon electrode, after various deposition times (s) as indicated, v=10 $mV.s^{-1}$. The deposition and onset potential is set at -1.4 V.

3.2. Chronoamperometric study of the electrochemical behavior of the ZnSe binary on a glassy electrode

Figure 10 shows the transient curves recorded from the system consisting of ChCl-U +10 mmol of SeO_2 + 50 mmol of $ZnSO_4.7H_2O$ at 100°C, on a GCE. To record these transient, the carbon electrode is subjected to a potential of -0.2V (E1) for 1 s, then to a second potential of -1.28 V (E2) for 5 s, and finally a variable potential E3 is applied for 20 s, from which a current vs.time transient is recorded each time. Generally chronoamperometric analysis of transients exhibits an ascending current that reaches a maximum from which the current decreases with time. Comparison of the curves obtained at different potentials shows that the current density corresponding to maximum current (j_{max}) increases as the potential tends toward negative values. At the same time, the corresponding current decreases with the potential. When the growth of the synthesized binary stops, the current decreases very rapidly, and the transients overlap, presenting a profile of a Cotrell-type diffusion controlled phenomenon.

To highlight the nucleation and growth mode that occurs during the formation of the ZnSe binary, the transient curves obtained were compared with those of the theoretical model of Scharifker and Hills (Scharifker et Hills, 1978). **Figure 11** presents the plot of the dimensionless experimental curves of the current density $(\frac{j}{j_{max}})^2$ as function of $(\frac{t}{t_{max}})$ obtained by using the transient data from **Figure 10**. These experimental curves are plotted in the same figure as the theoretical Scharifker and Hills curves for instantaneous and progressive 3D nucleation and growth according to equations (6) and (7).

In the case of instantaneous nucleation (IN)

$$\left(\frac{j}{j_{max}}\right)^2 = 1{,}9542 * \left(\frac{t_{max}}{t}\right) * \left\{1 - \exp\left[-1{,}2564 * \left(\frac{t}{t_{max}}\right)\right]\right\}^2 \quad (6)$$

In the case of progressive nucleation (PN)

$$\left(\frac{j}{j_{max}}\right)^2 = 1{,}2254 * \left(\frac{t_{max}}{t}\right) * \left\{1 - \exp\left[-2{,}3367 * \left(\frac{t}{t_{max}}\right)^2\right]\right\}^2 \quad (7)$$

The analysis of **Figure 11** below indicates that the shapes of the experimental curves follow the theoretical model of Scharifker and Hills for progressive three dimensional (3D) nucleation and growth. In short, the electrodeposition of ZnSe follows slow kinetics involving a progressive 3D nucleation and growth phenomenon. This suggests the synthesis of non-uniformly sized binaries.

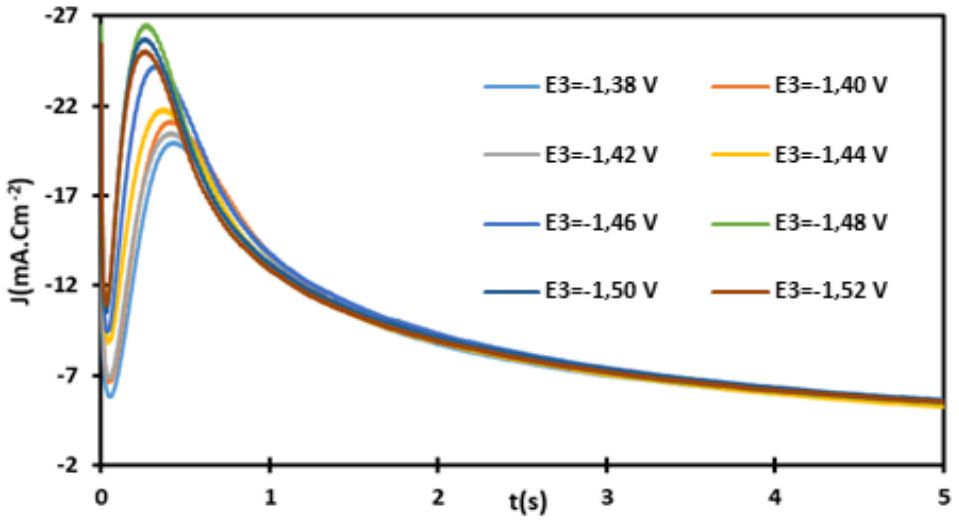

Figure 10: Transients recorded on a glassy carbon electrode in a ChCl-U +10 mmol of SeO_2 + 50 mmol of $ZnSO_4.7H_2O$ at T=100°C. Glassy carbon electrode subjected to E1=+1.2V, for t=1s, then jump to E2=-1.24 V for t=5s, then variation of E3.

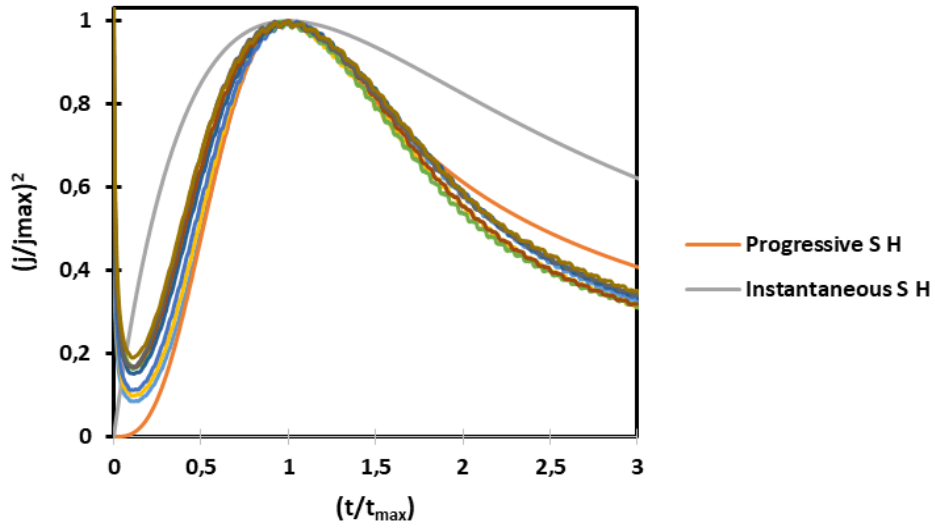

Figure 11: Comparative study of the dimensionless curves $(j/j_{max})^2=f(t/t_{max})$ of the transient current density recorded on a glassy carbon electrode in a solution of ChCl-U++10 mmol of SeO_2 + 50 mmol of $ZnSO_4.7H_2O$, with the theoretical model of Scharifker and Hills.

3.3. Characterization of ZnSe deposition

Figure 12 represents the SEM image of the synthesis of the ZnSe binary obtained on a glassy carbon electrode at -1.4 V under potentiostatic control for 780s. Two essential parts can be noted on the image. One part consists of whitishgreyish crystals in the form of veins that we attribute to the deposition of Se (0). A second part corresponds to a thin layer consisting of two black and whitish colored elements that would be linked to the deposition of the binary on the surface of the carbon electrode.

Figure 12: SEM image of ZnSe synthesis at 100°C.

Introducing the mixture of SeO_2 and $ZnSO_4.7H_2O$ into the ChCl-U medium (**Figure 13**) produces a colorless solution under magnetic stirring. The UV range with the least interference compared to other electromagnetic analysis techniques. The use of UV-visible spectroscopy measurement at 100°C identifies a well-defined absorption peak at 264 nm, which is thought to be related to the presence of the ZnSe species in the medium, in accordance with data from Venkatachalam and al. (Venkatachalam et *al* 2007) and Attia and al. (Attia and al et *al* 2019) in a molten salt medium**.** This result confirms and supports previous hypotheses on the synthesis of the ZnSe binary**.**

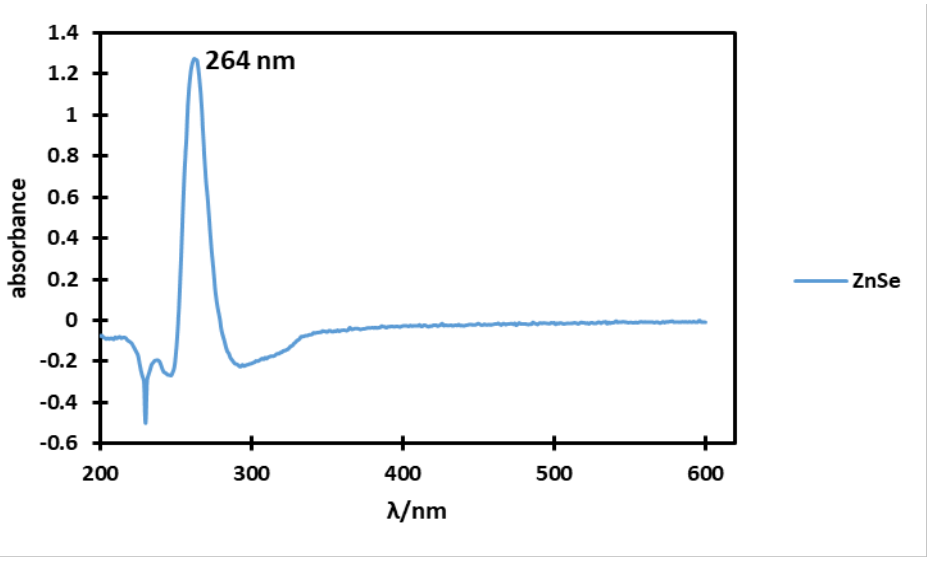

Figure 13: UV-visible spectra of the mixture of 10 mmol of SeO_2 and 50 mmol of $ZnSO_4.7H_2O$ in a ChCl-U medium.

Conclusion

This work consisted of the synthesis of the ZnSe binary in a choline chloride-urea medium at 100°C. The study of the interdependence of the cathode peaks made it possible to highlight the peak linked to the binary and to determine the equilibrium potential (-1.40 V) of the deposition of the two precursors salts during the formation of the binary. The ZnSe deposition peak appears at a potential of -1.30V. Time favors the deposition of selenide much more during the formation of the binary, which explains the presence of a greater electrodeposited charge of Se(0) during the redissolution of the deposit linked

to the synthesis of ZnSe.Chronoamperometric analysis confirms a progressive 3D deposition. The SEM image of the deposited layer shows non-uniform thin layers on the surface of the glassy carbon electrode, which are likely due to the presence of the ZnSe binary, as indicated by the UV-visible analysis.

References

Abbott A.P., Barron J. C., Frisch G., Gurman S., Ryder K. S. et Silva A., (2011), Double Layer Effects on Metal Nucleation in Deep Eutectic Solvents, *Phys. Chem*, 13, 10224–10231.

Abbott A. P., Capper G., Davies D. L., Rasheed R. K., et Tambyrajah V., (2003) « Novel solvent properties of choline chloride/urea mixtures », *Chem. Commun.*,1, 70-71, doi: 10.1039/b2a10714g.

Attia M.F. (2019), Study on Electrical, Optical Properties of ZnSe/SiO_2 Composite Thin Film Using Sol-Gel Dip Coating Techniques**,** *Journal of Materials Science Research and Reviews* 3, 1-13, Article no.JMSRR.47105.

Bazzi I., Hamdani I., Kadda S., Zaidi K., Merimi C., Loukili E. (2023). Corrosion inhibitors of mild steel in acidic solution: A bibliometric analysis from 1990 to 2023, *Afr. J. Manag. Engg. Technol.* 1 (1), 76-89.

Bernasconi R., Zebarjadi M., Magagnin L. (2015) Copper electrodeposition from a chloride free deep eutectic solvent, *J. Electroanal. Chem*, 758,163-169. https://doi.org/10.1016/j.jelechem.2015.10.024.

Bienkowski K, Strawski M, Maranowski B, Szklarczyk M. (2010), Studies of stoichiometry of electrochemically grown CdSe deposits. *Electrochimica Acta,* 55 (28), 8908.

Bougouma M., Doneux Th.,Legma J.B, Buess-Herman C. (2014)**,** Etude électrochimique du système Zn-Se en milieu eutectique chlorure de choline-urée, *J. Soc. Ouest-Afr. Chim,* 038, 1- 14.

Bougouma M., Van Elewyck A., Steichen M., Buess-Herman C., Doneux Th. (2013) Selenium electrochemistry in choline chloride–urea deep eutectic electrolyte**,** *J Solid State Electrochem.* 17, 527–536, https://doi.org/10.1007/s10008-012-1955-5

Bouroushian M, Karoussos D, Kosanovic T. (2006), Photoelectrochemical properties of electrodeposited CdSe and CdSe/ZnSe thin films in sulphide-polysulphide and ferroferricyanide redox systems. Solid State Ionics, 177(1925), 1855.

Bozzini B., Gianoncelli A., kaulich B., Mele Cl., Prasciolu M., Kiskinova M. (2012), Electrodeposition of manganese oxide from eutectic urea/choline chloride ionic liquid: An in situ study based on soft X-ray spectromicroscopy and visible reflectivity, *Journal of Power Sources,* 211, 71-76.

Bucko M., Tomic M. V., Maksimovic M., Bajat J. B., (2019). The importance of using hydrogen evolution inhibitor during the Zn and Zn-Mn electrodeposition from ethaline, *J. Serb.Chem. Soc*, 84, 1221-1234.

Chandramohan R, Sanjeeviraja C, Mahlingam T. (1997), Preparation of zinc selenide thin films by electrodeposition technique for solar cell applications. *Phys Stat Sol (a),* 163(2), R11.

Choi Y. H., van Spronsen J, Dai Y, Verberme M (2011), "Are Natural Deep Eutectic Solvents the Missing Link in Understanding Cellular Metabolism and Physiology?" *Plant Physiol*, 4, 1701–1705.

Cojocaru A.,Sin I.,Agapescu C,Cotarta A.,Visan T.,(2016),electrode processes and SEM/EDX analysis of selenium films electrodeposited from ionic liquids based on choline chloride, *Chalcogenide Letters*, 127 – 138.

Elafia Z., Messous Y.M., Hammouti B., Cherkaoui M. (2023) Synthesis and characterization of Mn/Ce-Doped TiO_2: Investigation of structural and optical properties, *Mor. J. Chem.,* 14(2), 350-360. doi.org/10.48317/IMIST.PRSM/morjchem-v11i2.35078

Faremi A.A., Akindadelo A.T., Adekoya M.A., Adebayo A.J., Salau A.O., Oluyamo S.S., Olubambi P. A. (2022). Engineering of window layer cadmium sulphide and zinc sulphide thin films for solar cell applications, *Results in Engineering*, 16, 100622, https://doi.org/10.1016/j.rineng.2022.100622.

Fernandez A.M., Turner J.A. (2003), Preparation and photocharacterization of Cu–Sb–Se films by electrodeposition technique. *Solar Energy Materials & Solar Cells,*79(3), 391-399.

Guo M.W., Sun C.B., Yang W.Q., Chen L., Lei H., Zhang Q.B. (2020), Sulphur-induced electrochemical synthesis of manganese nanoflakes from choline chloride/ethylene glycol-based deep eutectic solvent, *Electrochimica Acta*, 341, 136017.

Hammouti B., Aichouch I., Kachbou Y., Azzaoui K., Touzani R. (2025) Bibliometric analysis of global research trends on UMI using Scopus database and VOS viewer from 1987–2024, *J. Mater. Environ. Sci.,* 16(4), 548-561

Hankare PP, Chate PA, Chavan PA, Sathe DJ. (2008), Chemical deposition of ZnSe thin films: Photoelectrochemical applications. *Journal of Alloys and Compounds*. 461(1-2), 623.

Hao H, Yao X, Wang M. (2007), Preparation and optical characteristics of ZnSe nanocrystals doped glass by sol-gel in situ crystallization method. *Optical Materials.* 29(5), 573.

Harati M., Love D., Lau W. M., Ding Z., (2012) Preparation of crystalline zinc oxide films by one-step electrodeposition in Reline, *Materials Letters,* 89, 339–342.

Kadda S., Merzouki M., Alaloui M.M., Himri C. (2025). DFT and Docking Techniques: Bibliometric analysis, *Arab. J. Chem. Environ. Res.* 12 (2), 167-178

Kroger F.A. (1978) 'Cathodic Deposition and Characterization of Metallic or Semiconducting Binary Alloys or Compounds' *J. Electrochem. Soc.,* 125, 2028-2034.

Krishnam V, Ham D, Mishra KK, Rajeshwar K. (1992), Electrosynthesis of thin films of CdZnSe: composition modulation and bandgap engineering in the ternary system. *J Electrochem Soc,* 139(1):23.

Kumar SR, Nuthalapati M, Maity J. (2012), Development of nanocrystalline ZnSe thin film through electrodeposition from a non-aqueous solution. *Scripta Materialia,* 67(4), 396.

Li G, Nogami M. (1994), Preparation and optical properties of sol-gel derived ZnSe crystallites doped in glass films. *J Appl Phys,* 75(8), 4276.

Mann O, Pan GB, Freyland W. (2009), Nanoscale electrodeposition of metals and compound semiconductors from ionic liquids. *Electrochimica Acta*, 54(9), 2487

Metin H., Durmus S., Erat S., Ari M. (2011), Characterization of chemically deposited ZnSe/SnO_2/glass films: influence of annealing in Ar atmosphere on physical properties. *Applied Surface Science*, 15(257), 6474

Mirtat B.,Tatjana K.,Zafiris L.,Nicholas S. (2002), Electrochemical formation of zinc selenide from acidic aqueous solutions, *J. Solid State Electrochem*, 6, 272-278 DOI 10.1007/s100080100215

Moutari M.S., Kindo A., Fousséni S., Alassane. S., Moussa B., Giuseppina C., Philippe L. (2025), Electrodeposition of manganese in choline chloride-urea medium, *J. Mater. Environ. Sci.,* 16(2), 371-381.

Moutari M. S., Adama K., Bougouma M., Soma F., Sorgho A., Conti Gi, Leclere P. (2023), Temperature effect on zinc electrodeposition in choline chloride-urea deep eutectic solvent, *Mediterranean Journal of Chemistry,* 13, 228-239, DOI: http://dx.doi.org/10.13171/mjc02306161653bougouma.

Natarajan C, Sharon M, Levy-Clement C, Neumann-Spallart M. (1994), Electrodeposition of zinc selenide. *Thin Solid Films,* 12, 237, 118.

N'diaye A.D., Kankou M.S.A., Hammouti B., Nandiyanto A.B.D., Al Husaeni D.F. (2022). A review of biomaterial as an adsorbent: From the bibliometric literature review, the definition of dyes and adsorbent, the adsorption phenomena and isotherm models, factors affecting the adsorption process, to the use of typha species waste as adsorbent. *Communications in Science and Technology,* 7(2), 140-153. https://doi.org/10.21924/cst.7.2.2022.977.

Obeten M. E., Ugi B. U., Alobi N. O. (2017), A review on electrochemical properties of choline chloride based eutectic solvent in mineral processing, *J. Appl. Sci. Environ. Manage*, 21 991-998. https://doi.org/10.104314/jasem.v21i5.29.

Ramasamy K., Malik M.A., Revaprasadu N., O'Brien P. (2013), Routes to nanostructured inorganic materials with potential for solar energy applications, *Chem. Mater.* 25, 3551-3569, http://dx.doi.org/10.1021/cm401366q.

Rayée Q., Doneux T., Buess-Herman C.,(2017) Underpotential deposition of silver on gold from deep eutectic electrolytes, *Electrochimica Acta*,237, 127–132.

Riveros G, Lincot D, Guillemoles JF, Henriquez R, Schrebler R, Cordova R, Gomez H. (2003),Redox and solution chemistry of the SeSO32−-Zn-EDTA2− system and electrodeposition behavior of ZnSe from alkaline solutions. *Journal of Electroanalytical Chemistry*, 558, 9.

Romeo A, Artegiani E. (2021). CdTe-Based Thin Film Solar Cells: Past, Present and Future. *Energies.* 14(6):1684. https://doi.org/10.3390/en14061684

Samantilleke A.P., Boyle M.H., Young J., Dharmadasa I.M. (1998), Growth of n-type and p-type ZnSe thin films using an electrochemical technique for applications in large area optoelectronic devices. *Journal of Materials Science: Materials in Electronics*, 9(3), 231.

Sanchez S, Lucas C, Picard GS, Bermejo MR, Castrillejo Y. (2000), Molten salt route for ZnSe high-temperature electrosynthesis. *Thin Solid Films,* 107, 361-362.

Scharifker B., Hills G. (1983), Theoretical and experimental studies of multiple nucleation. *Electrochimica Acta,* 28**,** 879–889.

Sebastián P., Vallés E., Gómez E. *(*2013), First stages of silver electrodeposition in a deep eutectic solvent. Comparative behavior in aqueous medium, *Electrochim. Acta,* 112, 149–158, http://dx.doi.org/10.1016/j.electacta.2013.08.144 .

Sebastián P., Botello L.E., Vallés E., Gómez E., Palomar-Pardavé M., Scharifker B.R., Mostany J. (2016) Three-dimensional nucleation with diffusion-controlled growth: A comparative study of electrochemical phase formation from aqueous and deep eutectic solvents, *J. Electroanal. Chem,* 793, 119–125, http://dx.doi.org/10.1016/j.jelechem.2016.12.014 .

Sebastián P., Torralba E., Vallés E., Molina A., Gómez E. (2015), Advances in Copper Electrodeposition in Chloride Excess. A Theoretical and Experimental Approach, *Electrochimica Acta,* 164, 187-195. http://doi.org/10.1016/j.electacta.2015.02.206.

Smith L., Abbott A. P., Ryder K. S. (2014) « Deep eutectic solvents (DESs) and their applications », *Chem. Rev*, 21, 11060-11082 doi: 10.1021/cr300162p.

Venkatachalam S., Soundararajan D., Peranantham P., Mangalaraj D., Narayandass Sa.K., Velumani S., Schabes-Retchkiman P. (2007), Spectroscopic ellipsometry studies on vacuum-evaporated ZnSe thin films, *Materials Characterization* 58, 715–720 .

Vieira L., Schennach R., Gollas B. (2015), The Effect of the Electrode Material on the Electrodeposition of Zinc from Deep Eutectic Solvents, *Electrochimica Acta,* 197, 344-352, Http://Dx.Doi.Org/10.1016/j.Electacta.2015.11.030**.**

Wei C, Rajeswar K. (1992), Flow Electrosyntheses of group II–VI compound semiconductor thin films and composition-modulated superstructures. *J. Electrochem. Soc.* 139(4):L40.

Xueliang X., Xingli Z., Xionggang L., Changyuan L., Hongwei C.; Qian X.; Zhongfu Z. (2016), Electrodeposition of Zn and CuZn alloy from ZnO/CuO precursors in deep eutectic solvent*, Applied Surface Science*, *385*, 481-489, https://doi.org/10.1016/j.apsusc.

Yang H**.**, Reddy R.G., (2014), Electrochemical deposition of zinc from zinc oxide in 2 :1 urea/choline chloride ionic liquid, *Electrochim. Acta*, 147, 513–519.

Yushanjiang H., Liu R.Q., Mi H.Y. (2014), Electrodeposition behaviors of Cerium in ionic liquid. *Chinese Journal of Rare Metals,* 38(3), 432.