

Investigation of Material Selection for Electrochromic Application using MADM Techniques

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Abstract

This paper presents the selection of suitable metal oxide for electrochromic application. There is a need to select a suitable metal oxide that will give the desired optical properties. This research has applied two multiple-attribute-decision-making (MADM) methods to solve the material selection problem. The two methods used in this study are the technique for order preference by similarity to ideal solution (TOPSIS) method and Vise Kriterijumska Optimizacija Kompromisno Resenje (VIKOR). Opinions from the decision-makers obtain the weights to be used for these methods. A case problem to select the best metal oxide to be used in the electrochromic application is presented in this study to demonstrate the effectiveness of the proposed framework. Empirical results show that the proposed methods are viable approaches in solving the metal oxide selection problem. After using both, the method results show that Ta₂O₅ is the preferred alternative for electrochromic application.

Keywords: - Metal Oxide, Electrochromic, MADM, TOPSIS, VIKOR

INTRODUCTION

For the last two to three decades, electrochromic devices are of great technological importance due to their important applications. The phenomenon of electrochromism occurs in numerous inorganic and organic materials [1,2]. These materials are currently of considerable interest for newer technological aspects and the construction of electrochromic devices. Today, many materials are available that show a reversible colouration change on applying an electric field. Electrochromic materials are grouped into two main categories: organic materials and inorganic materials.

Inorganic material colouration change was observed due to electro-redox reaction, while inorganic materials were observed due to a double injection of ions and electrons [3,4]. Major organic electrochromic materials face two major issues: (i) Use of aqueous solution, which introduces water electrolysis, (ii) Due to soluble coloured products causes colour diffusion. In inorganic electrochromic materials, almost all the materials are oxides of transition series that form a thin film. Electrochromic materials are categorized into two types: Cathodic and Anodic electrochromic

materials. Cathodic materials change their colour under charge insertion or reduction process.

In contrast, anodic changes their colour under charge insertion or reduction process while anodic materials change their colour under charge extraction or oxidation process. WO_3 , TiO_2 , Nb_2O_5 , MoO_3 , and Ta_2O_5 are cathodic materials, while NiO , MnO_2 are anodic materials [5,6]. Out of all oxides, only some can be fully transparent to visible light, while others show absorption in visible light. Ideally, suitable electrochromic materials must satisfy the following criteria: Density, Bandgap, Refractive index and Molecular weight.

Multi-criteria decision making (MCDM) is the most commonly used technique to evaluate the alternatives based on the set of well-defined attributes. MCDM can further be categorized as multi-objective decision making (MODM) and Multi-attribute decision making (MADM). Several researchers have demonstrated the use of the MCDM technique to solve complex problems involving multiple criteria for decision-making. In the MODM technique, optimization is performed through prioritizing the objectives, while in the MADM technique, the best alternative is selected by prioritizing and ranking the set alternatives. MCDM technique plays a significant role in effective decision-making in small as well as large scale problems. Several MADM methods such as simple additive weighted (SAW) method, weighted product method (WPM), a technique for order preference by similarity to ideal solution (TOPSIS), Vise Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) method, analytical hierarchy process (AHP), graph theory and matrix representation approach (GTMA) etc.

has been by the researchers in the past [7-9]. Jee and Kang [10] applied a hybrid entropy TOPSIS technique to determine the best material for the flywheel. Shanian and Savadogo [11] solved the problem TOPSIS technique of selecting the most appropriate material for metallic bipolar plates using the TOPSIS technique. Chon and Tong [12] applied grey relational analysis to rank and chose the material to facilitate end-of-life (EOL) strategy. Rao [13] used an improved compromise ranking method to select the optimal material for an engineering application. Rao and Davim [14] used an integrated TOPSIS-AHP approach to select the most suitable material for a given application. Dagdeviren et al. [15] solved the weapon selection problem using a hybrid AHP-TOPSIS technique under a fuzzy environment. Chatterjee et al. [16] used an integrated VIKOR-ELECTRE approach to select the best material for different components. Fayazbakhsh et al. [17] applied the Z-transformation method to rank and select the best material for mechanical application. Khabbazi et al. [18] applied fuzzy logic approach to select the best material for application in mechanical engineering. Jahan et al. performed a literature review on the techniques used for determining the best material for engineering components. Their study proposed in comparison to MADM methods, linear assignment techniques are simple for selecting the material. However, the main limitation of this method is that it is less accurate than MADM methods, especially when the material selection is based on quantitative material properties. Rao and Patel [19] solved a material selection problem using a novel MADM method using fuzzy logic.

The present study aims to propose a systematic model for selecting the best suitable metal oxide for optical and electrochromic properties. The problem of metal oxide selection is considered a MADM problem where various criteria should be considered in decision making among a set of available alternatives. TOPSIS method uses vector normalization, whereas the VIKOR method uses linear normalization to convert different scales of different criteria into a standard. This paper is organized into four different sections: Sect.II describes the materials and methods adopted for MADM analysis. Sect.III describes the result and discussion for the MADM method and finally Sect.IV presented the conclusion of the material selection.

MATERIALS AND METHODS FOR MDM

The flow chart shown in Fig.1 describes the

various steps considered to find the best metal oxide among all. The parameter considered for selection of best metal oxide is density (g/cm³), bandgap (eV), refractive index and molar mass (g/mol). The selected parameters are given in Table.1.

TOPICS METHOD

The TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) was first developed by H.C.Lai and K.Yoon in 1981[20].

By this method, the best alternative is found by finding the ideal solution from shortest Euclidean distance and the worst solution from farthest distance [21]. In the past, lots of studies have been carried out using the TOPSIS method for MADM problems [22-26]. The general procedure consists of the following steps:

Table 1 Properties of Metal Oxide for Electrochromic Devices

Metal Oxide	Density (g/cm ³)	Band Gap (eV)	Refractive Index	Molar mass (g/mol)
ZnO	5.61	3.30	2.01	81.41
WO ₃	7.16	2.60	2.10	231.84
MoO ₃	4.70	3.40	2.03	143.95
TiO ₂	4.23	3.05	2.58	79.87
Nb ₂ O ₅	4.60	3.40	2.32	265.81
NiO	6.67	3.60	2.18	74.69
MnO ₂	5.03	1.33	2.16	86.93
Ta ₂ O ₅	8.37	5.30	2.28	441.89

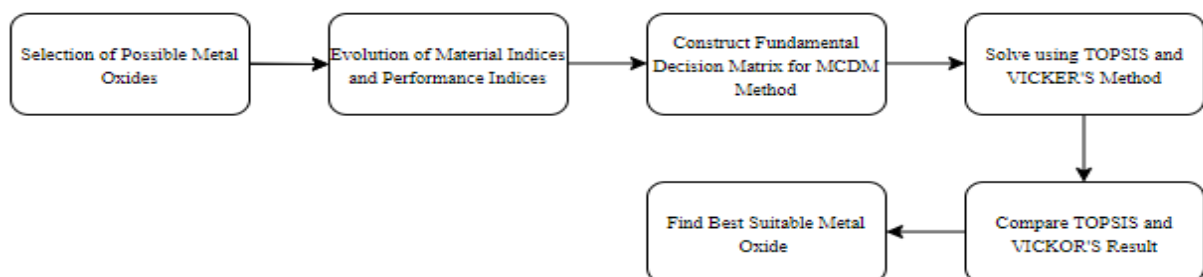


Figure 1 Selection Method for Metal Oxide

Step: 1 Prepare a decision matrix for the ranking in which columns indicate criteria or attributes ($C_1, C_2, C_3, \dots, C_n$) while rows indicate alternatives ($A_1, A_2, A_3, \dots, A_m$). An element x_{ij} of the matrix indicates the performance rating of the i^{th} alternative, A_i , concerning the j^{th} criteria C_j , as shown in Eq.(1),

$$\begin{matrix} & C_1 & C_2 & C_3 & - & C_n \\ \begin{matrix} A_1 \\ A_2 \\ A_3 \\ - \\ - \\ A_m \end{matrix} & \begin{bmatrix} x_{11} & x_{12} & x_{13} & - & x_{1n} \\ x_{21} & x_{22} & x_{23} & - & x_{2n} \\ x_{31} & x_{32} & x_{33} & - & x_{3n} \\ - & - & - & - & - \\ - & - & - & - & - \\ x_{m1} & x_{m2} & x_{m3} & - & x_{mn} \end{bmatrix} \end{matrix} \quad (1)$$

Step: 2 Calculate normalized rating for each element in the decision matrix. The normalized value r_{ij} of x_{ij} is calculated as defined in Eq. (2).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}, \quad i=1, 2, \dots, m; j=1, 2, \dots, n \quad (2)$$

Step: 3 Calculate weighted normalized value v_{ij} by multiplying the normalized decision matrix by its associated weights, obtained by decision-maker makes.

Step: 4 Determine positive ideal (V^+) and negative ideal solutions (V^-). The ideal (best) and negative ideal (worst) solutions can be expressed as:

$$V^+ = \left\{ \left(\sum_i^{\max} v_{ij} / j \in J \right), \left(\sum_i^{\min} v_{ij} / j \in J' \right), i = 1, 2, \dots, m \right\} \quad (3)$$

$$V^- = \left\{ \left(\sum_i^{\min} v_{ij} / j \in J \right), \left(\sum_i^{\max} v_{ij} / j \in J' \right), i = 1, 2, \dots, m \right\} \quad (4)$$

Where, $J = (j = 1, 2, \dots, n)$ is set of beneficial criteria (larger the-better type) and $J' = (j = 1, 2, \dots, n)$ is set of non-beneficial criteria (small-the-better type).

Step: 5 Obtain separation measures. The n -dimensional Euclidean distance can measure the separation (distance) between alternatives. The separation of each alternative from the positive-ideal solution is given as

$$S_i^+ = \sqrt{\sum_{j=1}^n v_{ij} - v_j^{+2}}, \quad i = 1, 2, \dots, m \quad (5)$$

$$S_i^- = \sqrt{\sum_{j=1}^n v_{ij} - v_j^{-2}}, \quad i = 1, 2, \dots, m \quad (6)$$

Similarly, the separation from the negative ideal solution is as follows:

Step: 6 Calculate the relative closeness to ideal solution. The relative closeness of the alternative A_{ij} can be expressed as:

$$R_i = \frac{S_i^-}{S_i^+ - S_i^-} \quad (7)$$

Step: 7 Choose an alternative with maximum R_i or rank alternatives according to R_i in descending order.

VIKOR METHOD

Opricovic developed the VIKOR method in 1998 [27]. However, Chang developed a modified VIKOR method to simplify the calculations. This method also focuses on ranking and selecting the best alternative same as the TOPSIS method. TOPSIS method is based on vector normalization, whereas the VIKOR method is linear normalization. The formal VIKOR method consists of the following steps:

Step 1: Determine the ideal and negative ideal solutions. As a minimization problem is dealt with in this paper, the ideal solution A^* and the negative ideal solution A^- are computed as follows:

$$A^* = \min\{f_{ij} \mid i = 1, 2, \dots, m\} \\ = \{f_1^*, f_2^*, \dots, f_n^*\} \quad (8)$$

$$A^- = \max\{f_{ij} \mid i = 1, 2, \dots, m\} \\ = \{f_1^-, f_2^-, \dots, f_n^-\} \quad (9)$$

Step: 2 Calculate the utility measure and the regret measure. The utility measure and the regret measure for each non-dominated solution can be expressed as:

$$S_i = \sum_{j=1}^v w_j \left(\frac{x_j^* - x_{ij}}{x_j^* - x_j^-} \right) \quad (10)$$

$$R_i = \max_j \left[w_j \left(\frac{x_j^* - x_{ij}}{x_j^* - x_j^-} \right) \right] \quad (11)$$

Where, $S_i, R_i \in [0, 1]$, 0 denotes the best and 1 denotes the worst situations. w_j is the weight of the criteria, and $\sum_{j=1}^v w_j = 1$.

Step: 3 Calculate Q_i for i^{th} alternative where $i=1, 2, 3, \dots, n$. This is done using the equation,

$$Q_i = \alpha \frac{(S_i - S^*)}{(S^- - S^*)} + (1-\alpha) \frac{(R_i - R^*)}{(R^- - R^*)} \quad (12)$$

Where $\alpha \in [0, 1]$ is a weighting factor and is usually selected to be 0.5.

Step: 4 Find out the best suitable value of S_i, R_i , and Q_i in increasing order.

Step: 5 Now decide the best alternative ranked from the flow chart given below:

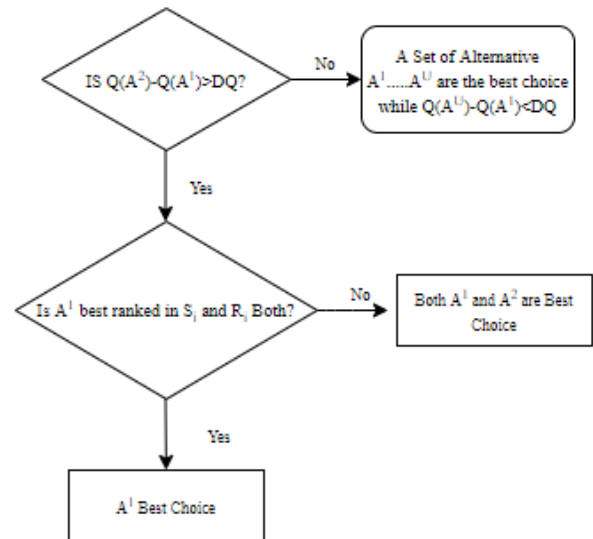


Figure 2 Decision flow chart for VIKOR Method [15].

RESULT AND DISCUSSION

The value of density, band gap, refractive index and molar weight for metal oxides can be found easily in literature. Now, to demonstrate the proposed method for selecting better metal oxide for electrochromic applications, composed of TOPSIS and VIKOR approach.

3.1 TOPSIS Method

The decision matrix is to be established by comparing alternatives under each of the criteria in Table. 2.

Table 2 Objective Data with Decision Matrix

Alternatives	Density (g/cm ³)	Band Gap (eV)	Refractive Index	Molar mass (g/mol)
A ₁	5.61	3.30	2.01	81.41
A ₂	7.16	2.60	2.10	231.84
A ₃	4.70	3.40	2.03	143.95
A ₄	4.23	3.05	2.58	79.87
A ₅	4.60	3.40	2.32	265.81
A ₆	6.67	3.60	2.18	74.69
A ₇	5.03	1.33	2.16	86.93
A ₈	8.37	5.30	2.28	441.89

The decision matrix is shown below: Based on the TOPSIS method mentioned in Section 2.1, each element is normalized by Eq. (2).

Table 3 Normalized TOPSIS Decision Matrix

Alternatives	Density (g/cm ³)	Band Gap (eV)	Refractive Index	Molar mass (g/mol)
A ₁	0.3331	0.3424	0.3215	0.1345
A ₂	0.4251	0.2698	0.3354	0.3829
A ₃	0.2790	0.3528	0.3242	0.2378
A ₄	0.2511	0.3165	0.4121	0.1319
A ₅	0.2731	0.3528	0.3697	0.4391
A ₆	0.3960	0.3735	0.3485	0.1234
A ₇	0.2984	0.3450	0.3450	0.1436
A ₈	0.4969	0.3634	0.3634	0.7299
Weights	0.2	0.4	0.3	0.1

The resulting normalized decision matrix for the TOPSIS analysis is shown in Table.3.

Table 4 Weighted Normalized TOPSIS Decision Matrix

Alternatives	Density (g/cm ³)	Band Gap (eV)	Refractive Index	Molar mass (g/mol)
A ₁	0.0666	0.1370	0.0965	0.0134
A ₂	0.0850	0.1079	0.1006	0.0383
A ₃	0.0558	0.1411	0.0973	0.0238
A ₄	0.0502	0.1266	0.1236	0.0132
A ₅	0.0546	0.1411	0.1109	0.0439
A ₆	0.0792	0.1494	0.1045	0.0123
A ₇	0.0597	0.0552	0.1035	0.0144
A ₈	0.0994	0.2200	0.1090	0.0730

The next step is the formation of a weighted normalized matrix using weights {(0.2), (0.4),(0.3), and (0.1)} of the criteria obtained by the decision-maker makes. The resultant weighted normalized matrix is given in table.4.

Finally, the rank is given to alternatives according to relative closeness to the ideal solution (Ri) using Eq. (7). The given ranks are shown in table 5.

Table 5 Ranking of alternatives by TOPSIS Method

Alternatives	Metal Oxide	Si ⁺	Si ⁻	Ri	Rank
A ₁	ZnO	0.0933	0.1025	0.5234	A ₃
A ₂	WO ₃	0.1182	0.0722	0.3792	A ₇
A ₃	MoO ₃	0.0946	0.0992	0.5119	A ₄
A ₄	TiO ₂	0.1055	0.0970	0.4789	A ₆

A ₅	Nb ₂ O ₅	0.0968	0.0920	0.4870	A ₅
A ₆	NiO	0.0758	0.1160	0.6047	A ₂
A ₇	MnO ₂	0.1707	0.0598	0.2595	A ₈
A ₈	Ta ₂ O ₅	0.0624	0.1724	0.7343	A ₁

3.2 VIKOR Method

The decision matrix from Table 3 is again used for the VIKOR analysis. The ideal solution is obtained by using Eq. (8) and Eq. (9).

Table 6 Ranking of alternatives by VIKOR Method

Alternatives	Metal Oxide	Si	Ri	Qi	VIKOR Ranking
A ₁	ZnO	0.7330	0.3000	0.6880	A ₇
A ₂	WO ₃	0.6417	0.2720	0.5659	A ₅
A ₃	MoO ₃	0.7409	0.2910	0.6746	A ₆
A ₄	TiO ₂	0.5253	0.2267	0.3899	A ₄
A ₅	Nb ₂ O ₅	0.5617	0.1914	0.3414	A ₂
A ₆	NiO	0.5641	0.2107	0.3834	A ₃
A ₇	MnO ₂	0.1614	0.1614	1.0000	A ₈
A ₈	Ta ₂ O ₅	0.8804	0.4000	0.0000	A ₁

The utility measure and the regret measure are calculated from Eq. (10) and (11). Finally, Qi is calculated from Eq. (12), showing the best metal oxide alternative. The calculated parameters are shown in table 6.

CONCLUSIONS

Proper selection of the metal oxide depends on the band gap for optical and electrochromic application. Many researchers used metal oxides for electrochromic application depending upon their experience and availability of the material. However, several alternatives must be considered and used in terms of many different criteria. So, the effective and proper method needs to be used to improve decision quality.

This paper proposes two MADM methods, TOPSIS and VIKOR, to determine the best metal oxide for electrochromic application. Both methods used weights assigned by decision-makers. After using both, the method results show

Ta₂O₅ as the preferred alternative. In short, the proposed method gives a systematic approach to narrow down the number of alternatives.

REFERENCES

1. Bhaskar, S. V. and Kudal, H. N. (2019). Multi-criteria decision-making approach to material selection in a tribological application. *International Journal of Operational Research*, 36(1), 92-122.
2. Chan, J.W. and Tong, T.K. (2007). 'Multi-criteria material selections and end-of-life product strategy: Grey relational analysis approach', *Materials & Design*, Vol. 28, No. 5, pp. 1539-1546.
3. Chatterjee, P., Athawale, V.M. and Chakraborty, S. (2009). 'Selection of materials using compromise ranking and outranking methods', *Materials & Design*, Vol. 30, No. 10, pp. 4043-4053.
4. Chen, C.T. (2000). 'Extensions of the TOPSIS for group decision-making under fuzzy environment', *Fuzzy Sets and Systems*, Vol. 114, No. 1, pp. 1-9.
5. Chen, S.J. and Hwang, C.L. (1992). 'Fuzzy multiple attribute decision-making methods, In *Fuzzy Multiple Attribute Decision Making* (pp. 289-486). Springer, Berlin, Heidelberg.
6. Chu, T.C. (2002). 'Selecting plant location via a fuzzy TOPSIS approach', *The International Journal of Advanced Manufacturing Technology*, Vol. 20, No. 11, pp. 859-864.
7. Chu, T.C., and Lin, Y.C. (2002). 'Improved extensions of the TOPSIS for group decision making under fuzzy environment', *Journal of Information and Optimization Sciences*, Vol. 23, No. 2, pp. 273-286.
8. Da Silva, A.J.C., Nogueira, F.A.R., Tonholo, J. and Ribeiro, A.S. (2011). 'Dual-type electrochromic device based on polypyrrole and polythiophene derivatives, *Solar Energy Materials and Solar Cells*, Vol. 95, No. 8, pp. 2255-2259.
9. Dagdeviren, M., Yavuz, S. and Kılınç, N. (2009). 'Weapon selection using the AHP and TOPSIS methods under fuzzy environment', *Expert Systems with Applications*, Vol. 36, No. 4, pp. 8143-8151.
10. Ertuğrul, İ. and Karakaşoğlu, N. (2009). 'Performance evaluation of Turkish cement firms with fuzzy analytic hierarchy process and TOPSIS methods', *Expert Systems with Applications*, Vol. 36, No. 1, pp. 702-715.
11. Fayazbakhsh, K., Abedian, A., Manshadi, B.D. and Khabbaz, R.S. (2009). 'Introducing a novel method for materials selection in mechanical design using Z-transformation in statistics for normalization of material properties', *Materials & Design*, Vol. 30, No. 10, pp. 4396-4404.
12. Granqvist, C. G. (Ed.). (1995). *Handbook of inorganic electrochromic materials*. Elsevier.
13. Hwang, C. and Yoon, K. (1981) *Multiple Attribute Decision Making Methods and Applications*, 1st ed., Springer-Verlag, Berlin; Heidelberg.
14. Jee, D.H. and Kang, K.J. (2000). 'A method for optimal material selection aided with decision-making theory', *Materials & Design*, Vol. 21, No. 3, pp. 199-206.
15. Kandpal, K. and Gupta, N. (2016). 'Investigations on high-κ dielectrics for low threshold voltage and low leakage zinc oxide thin-film transistor, using material selection methodologies', *Journal of Materials Science: Materials in Electronics*, Vol. 27, No. 6, pp. 5972-5981.
16. Khabbaz, R.S., Manshadi, B.D., Abedian, A. and Mahmudi, R. (2009). 'A simplified fuzzy logic approach for materials selection in mechanical engineering design', *Materials & Design*, Vol. 30, No. 3, pp. 687-697.
17. Monk, P.M., Mortimer, R.J. and Rosseinsky, D. R. (2008). 'Electrochromism: fundamentals and applications. John Wiley & Sons.
18. Opricovic, S. (1998). 'Multi-criteria optimization of civil engineering systems, *Faculty of Civil Engineering, Belgrade*, Vol. 2, No. 1, pp. 5-21.
19. Papaefthimiou, S., Leftheriotis, G. and Yianoulis, P. (1998). 'Electrochromic phenomena in transition

- metal oxide thin films prepared by thermal evaporation, *Ionics*, Vol. 4, No. 5-6, pp. 321-329.
20. Rao, R.V. (2007). Decision making in the manufacturing environment: using graph theory and fuzzy multiple attribute decision making methods. Springer Science & Business Media.
 21. Rao, R.V. (2008). 'A decision-making methodology for material selection using an improved compromise ranking method', *Materials & Design*, Vol. 29, No. 10, pp. 1949-1954.
 22. Rao, R.V. and Davim, J.P. (2008). 'A decision-making framework model for material selection using a combined multiple attribute decision-making method,' *The International Journal of Advanced Manufacturing Technology*, Vol. 35, No. 7-8, pp. 751-760.
 23. Rao, R.V. and Patel, B.K. (2010). 'A subjective and objective integrated multiple attribute decision-making method for material selection', *Materials & Design*, Vol. 31, No. 10, pp. 4738-4747.
 24. Rathod, M.K. and Kanzaria, H.V. (2011). 'A methodological concept for phase change material selection based on multiple criteria decision analysis with and without fuzzy environment,' *Materials & Design*, Vol. 32, No. 6, pp. 3578-3585.
 25. Shanian, A. and Savadogo, O. (2006). 'TOPSIS multiple-criteria decision support analysis for material selection of metallic bipolar plates for polymer electrolyte fuel cell', *Journal of Power Sources*, Vol. 159, No. 2, pp. 1095-1104.
 26. Wang, J., Liu, S.Y. and Zhang, J. (2005). 'An extension of TOPSIS for fuzzy MCDM based on vague set theory, *Journal of Systems Science and Systems Engineering*, Vol. 14, No. 1, pp. 73-84.
 27. Zhang, Q.Y., Wu, G.M., Zhou, B., Shen, J., Wang, J., Wu, Z.G. and Ji, X.H. (2001). 'Electrochromic properties of sol-gel deposited V2O5 and TiO2-V2O5 binary thin films', *Journal of Materials Science & Technology*, Vol. 17, No. 4, pp. 417-420.