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# APPLYING FACTOR ANALYSIS FOR ASSESSING KNOWLEDGE STRUCTURE OF STUDENTS IN GRADE 10: THE SUBJECT OF REDOX REACTION

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**Abstract.** *Redox reaction is an important concept in chemistry, and a well-organized knowledge structure of redox reaction is beneficial for concept learning. This study investigated the knowledge structure regarding redox reaction from 459 Grade 10 students. The pool of 15 redox reaction concepts was developed by content analysis, questionnaire survey, and interview. Six initial competing models with 15 concepts were identified via exploratory factor analysis (EFA) and paper-pencil test. Confirmatory factor analysis (CFA) was conducted to test and modify the six competing models according to the rating data of the students. As a result, six modified models fit the data well. However, the high inter-factor correlations indicate that the two- and three-factor models are the students' knowledge structures of redox reaction. The two-factor model is comprised of two distinct but correlated factors: the process of redox reaction and metrology. The three-factor model is comprised of three factors: the process of redox reaction, reaction ability, and metrology. The finding inflects the abstract relationships between the concepts related to redox reaction in students' minds.*

**Keywords:** *redox reaction, chemistry education, knowledge structure, factor analysis*

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## Introduction

The nature of knowledge is structure (Nakiboglu, 2008). Students need to comprehend the meanings and interrelationships of the related concepts to comprehend and acquire knowledge about a topic (Qian, 2008). After students cognitively process these interrelated concepts, these concepts will be stored in their minds in a certain organizational form, which is the knowledge structure (Burrows & Mooring, 2015). Scientific, logical, and explicit knowledge structures are easier to invoke, allowing students to execute relevant tasks with greater flexibility and speed. In many studies, knowledge structure is also called conceptual structure (Kurt, 2013a, 2013b) or cognitive structure (Atabek-Yigit, 2015; Gercek, 2018; Tasci & Yurdugul, 2017).

Chemistry knowledge encompasses a vast array of topics, each covering many related concepts. Students who do not understand the significance of and connections between related concepts can't fully grasp a topic (Nakiboglu, 2008). Redox reaction is widely regarded as one of the most difficult chemistry subjects in the teaching and learning process (Chiang et al., 2014; Qian, 2009). The topic of redox reaction contains many concepts that are textually similar but have different meanings, which confuses students and makes it difficult to correctly understand the meanings and interrelationships of the concepts (Delisma et al., 2019).

Moreover, one reason that students struggle in advanced courses such as electrochemistry is that their knowledge structures of redox reaction are inadequate and incoherent (Burrows & Mooring, 2015). Therefore, it is critical to reveal how students comprehend and organize the concepts related to redox reaction, that is, the knowledge structure of redox reaction.

The existing literature on redox reaction focuses on revealing misconceptions of students (Brandriet & Bretz, 2014b; Ferouni et al., 2012; Masykuri



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et al., 2019), the effects of a certain teaching intervention (Basheer et al., 2017; Cole et al., 2019; Seyhan et al., 2008; Syawal & Amanatie, 2019), and the development of inventories on examining the psychometric properties (Jin et al., 2020), understandings and confidence of students (Brandriet & Bretz, 2014a). However, few studies have examined the knowledge structure of redox reaction held by students (Chiang et al., 2014), especially using factor analysis.

*Knowledge Structure and Factor Analysis*

In the literature, a variety of research methods have been conducted on the study of knowledge structure in science education. The methods include concept map (Adamov et al., 2009; Burrows & Mooring, 2015; Chiang et al., 2014), word association (Bahar & Tongac, 2009; Nakiboglu, 2008), phenomenological approach (Choi & Oh, 2021; Tóth & Ludányi, 2007), think-aloud interview (Ahmadian et al., 2019; King et al., 2022), multi-dimensional scaling (MDS) (Chiou & Anderson, 2010; Tilga et al., 2017), knowledge space theory (Segedinac et al., 2018), pathfinder network algorithm (Casas-Garcia & Luengo-Gonzalez, 2013), factor analysis (Mai, Qian, Li et al., 2021), and reaction time technique (Mai, Qian, Lan et al., 2021).

It is worth noting that factor analysis has long been an important statistical tool in the social sciences (Montoya & Edwards, 2021), but is rarely used in science education. Recently, Mai, Qian, Li et al. (2021) has successfully used factor analysis for uncovering students' conceptual structure regarding chemical equilibrium. Additional studies are still necessary, especially in chemistry, that examine factor analysis as an assessment tool (Burrows & Mooring, 2015; Tóth & Ludányi, 2007). As such, we used factor analysis to explore students' knowledge structure of redox reaction.

Factor analysis is a statistical technique to extract common factors from variables, which can reveal the latent and representative factors among various variables. Factor analysis is comprised of exploratory factor analysis (EFA) and confirmatory factor analysis (CFA). EFA is a critical analysis to reveal the unknown relationship between observed and latent variables (Toma, 2021), whereas CFA is the subsequent level of analysis to test, compare, and modify the models derived from EFA or theoretical assumptions (Hair, et al., 2010; Harrington, 2009).

Researchers generally use CFA to test whether the data match the existing models (Chan et al., 2022). If no model has been proposed, EFA can be used to explore the relationships between variables (model), and then CFA is employed to test and modify the model (Alotaibi & Alotaibi, 2021; Pereira et al., 2021). This research adopted the latter analytical procedure since there is no literature on using factor analysis to investigate the relationships between the concepts related to redox reaction.

The instrument used for factor analysis is a rating scale. In the study focusing on the knowledge structure of science education, the items in the rating scale are usually concepts highly related to a certain topic (the concept pool). A high-quality concept pool is critical in knowledge structure research. A concept pool containing multiple and chaotic concepts may obscure vital information about the knowledge structure, while few and incomplete concepts cannot reveal the comprehensive picture of the knowledge structure.

In previous studies, researchers have selected a few concepts as the concept pool of redox reaction based on experience (Chiang et al., 2014; Jin et al., 2020), making it difficult to obtain a meaningful and comprehensive structure. Moreover, the negative effects of personal subjective judgment of such a concept pool are so strong that the knowledge structure is difficult to genuinely reflect the objective reality in students' minds. Therefore, it is important to obtain an objective and unbiased concept pool of redox reaction before exploring the knowledge structure held by students.

*Research Questions*

Existing literature lacks the use of factor analysis to explore the knowledge structure of redox reaction and lacks an objective and unbiased concept pool of redox reaction. An appropriate concept pool improves the quality of the knowledge structure. This research aimed to utilize factor analysis to reveal tenth-grade students' knowledge structure of redox reaction. The specific research issues that this research tried to answer were as follows.

1. What is the concept pool of redox reaction?
2. What is the knowledge structure of redox reaction acquired by students in Grade 10?


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**Research Methodology**

*General Background*

This research was a quantitative survey in which 333 upper-secondary school chemistry teachers, 36 postgraduate students, 8 chemistry professors, and 459 tenth-grade students in China participated during the 2017-2021 academic year. This research was separated into two sections. In the first section, the concept pool of redox reaction was established through content analysis, questionnaire survey, and interview. In the second section, initial competing models were identified via EFA and paper-pencil test, and then were tested and modified by CFA with the rating data of tenth-grade students.

*Participants*

This study included six samples of participants. Their demographic information is presented in Table 1. The data from six samples were utilized to create the concept pool of redox reaction. Meanwhile, the data from Sample 6 were also analyzed by factor analysis to obtain knowledge structure of redox reaction.

Samples 1, 2, and 5 were upper-secondary school chemistry teachers from all over China. Sample 3 consisted of postgraduate students majoring in Chemistry Teacher Education at South China Normal University, and Sample 4 was composed of chemistry professors at South China Normal University. Grade 10 students in Sample 6 from five upper-secondary schools were involved in this study after they had learned the content of redox reaction in the compulsory curriculum of chemistry. For the sake of convenience, the following text will refer to upper-secondary school students in Grade 10 as students and upper-secondary school chemistry teachers as teachers.

Based on the authors' explanation, all participants understood the purpose of the current study and volunteered to take part.

**Table 1**
*Participants' Demographic Information*

| Sample | N | Recovery rate (%) | Age | | Gender | | Teaching experience | |
|---|---|---|---|---|---|---|---|---|
| | | | *M* | *SD* | Male | Female | *M* | *SD* |
| Sample 1 | 76 | 76.0 | 34.07 | 5.56 | 42 | 34 | 17.92 | 6.22 |
| Sample 2 | 91 | 91.0 | 34.19 | 5.34 | 51 | 40 | 17.68 | 6.06 |
| Sample 3 | 36 | 90.0 | 24.17 | 1.18 | 2 | 34 | - | - |
| Sample 4 | 8 | - | 47.75 | 4.27 | 6 | 2 | 19.75 | 3.24 |
| Sample 5 | 166 | 66.4 | 38.86 | 7.44 | 102 | 64 | 17.99 | 6.10 |
| Sample 6 | 459 | 76.7 | 15.03 | .51 | 251 | 208 | - | - |

*Instruments and Procedures*

The instruments in this study were an open-ended questionnaire and two 7-point Likert scales. To collect the concepts related to redox reaction, content analysis and an open-ended questionnaire survey were conducted. Thirty-eight concepts were collected through content analysis. The contents included three versions of Chinese upper-secondary school chemistry compulsory textbooks (Song, 2007; Wang, 2007; Wang, 2014), chemistry curriculum standard of China (MOE, 2003), and the examination syllabus (National Education Examinations Authority, 2017). Besides, 30 concepts were elicited from 76 teachers (Sample 1) by an open-ended questionnaire survey. After sorting out the above-mentioned results and removing duplicates, 41 concepts were collected as items.

Three efforts had been done to screen concepts. First, a 7-point Likert scale comprised of 41 items was developed and distributed to 91 teachers (Sample 2) and 36 postgraduate students (Sample 3). They were asked to rate the relatedness between 41 items and oxidation-reduction reaction, ranging from 1 (the least relevant) to 7


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(the most relevant). Taking the average score > 5 as the cut-off, 32 items were obtained.

Second, 8 chemistry professors (Sample 4) and 10 teachers from Sample 1 agreed to verify the results and identify the concepts most related to redox reaction in an interview. As a consequence, 16 concepts were sorted out from 32 concepts.

Third, a 7-point Likert scale with 16 items was delivered to 166 teachers (Sample 5) and 459 students (Sample 6), who were asked to value the relatedness between 16 items and redox reaction, ranging from 1 (the least relevant) to 7 (the most relevant). By taking the average score > 5 as the standard, 15 items were eventually identified and recognized as the concept pool of redox reaction.

The knowledge structure regarding redox reaction of students was obtained in two steps. To begin, six rival models were identified via EFA and paper-pencil test. Furthermore, CFA was conducted to test and modify the six rival models.

### *Data Analysis*

According to the rating data of the four samples (Sample 2, 3, 5, and 6), descriptive statistics of SPSS 21.0 was employed to calculate the average scores of items. Researchers inspected the rating data and discovered that full scale (from 1 to 7) had been used by both teachers and students. The items with an average score of greater than 5 were used to determine the concepts related to redox reaction.

459 students (Sample 6) were randomly divided into two groups (Sample 6a and Sample 6b). The data from Sample 6a ($N$=230) were analyzed with EFA to explore the relationships between variables (model). The initial factors and their model were extracted using the principal axis factoring and Promax rotation method in SPSS 21.0. The data from Sample 6b ($N$=229) were analyzed with CFA to test and modify the models acquired by EFA and paper-pencil test (Pereira et al., 2021). The model parameters were estimated by employing the Robust Maximum Likelihood Estimation (MLR) of Mplus 7 (Mai, Qian, Li et al., 2021).

## Research Results

### *The Concept Pool of Redox Reaction*

Through content analysis and an open-ended questionnaire, 41 concepts were collected. A total of 26 concepts were deleted through three rounds of concept screening.

Nine items with an average score of less than 5 were deleted in the first round, and in the second round, 16 items were eliminated according to the suggestions of teachers and professors, as shown in Table 2. The items "double-track bridge method" and "single-track bridge method" are the methods summarized by Chinese upper-secondary school chemistry teachers to express the electron transfer in a redox reaction.

In the final round, the item "metallic corrosion" was eliminated since its average scores given by both teachers and students are less than 5, as shown in Table 3. In the end, the remaining 15 concepts were regarded as the concept pool of redox reaction. These concepts were coded in Table 3 for the convenience of subsequent research.

It is worth noting that the concept "conservation of gain and loss electrons" refers to the fact that the number of gain electrons equals the number of loss electrons in a redox reaction. This concept is summarized by Chinese upper-secondary school chemistry teachers. Students are familiar with this concept because it is utilized frequently in the practice of chemistry teaching in upper-secondary schools in China.

**Table 2**
*The Deleting Items in the First and Second Rounds of Concept Screening*

| Item | Round | Item | Round |
|---|---|---|---|
| Double-track bridge method | First | Strong reducing agent | Second |
| Single-track bridge method | First | Weak reducing agent | Second |
| Endothermic reaction | First | Strong reducing ability | Second |
| Exothermic reaction | First | Weak reducing ability | Second |


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| Item | Round | Item | Round |
|---|---|---|---|
| Maximum oxidation number | First | Combustion | Second |
| Minimum oxidation number | First | Explosion | Second |
| Energy | First | Metal activity | Second |
| Smelting | First | Slow oxidation | Second |
| Balancing equations | First | Gain of oxygen | Second |
| Strong oxidizing agent | Second | Loss of oxygen | Second |
| Weak oxidizing agent | Second | Oxidizing | Second |
| Strong oxidizing ability | Second | Reducing | Second |
| Weak oxidizing ability | Second | | |

**Table 3**
*The Average Scores of Items in the Survey*

| Code | Item | Teachers | | Students | |
|---|---|---|---|---|---|
| | | *M* | *SD* | *M* | *SD* |
| 1 | Conservation of gain and loss electrons | 6.56 | .87 | 6.12 | 1.33 |
| 2 | Electron transfer | 6.47 | .96 | 6.04 | 1.31 |
| 3 | Oxidizing ability | 6.17 | 1.27 | 5.63 | 1.45 |
| 4 | Oxidizing agent | 6.01 | 1.21 | 5.57 | 1.46 |
| 5 | Number of gain and loss electrons | 5.99 | 1.23 | 5.86 | 1.40 |
| 6 | Oxidation numbers | 5.98 | 1.34 | 5.63 | 1.56 |
| 7 | Oxidation state changes | 5.86 | 1.34 | 5.88 | 1.40 |
| 8 | Reducing agent | 5.71 | 1.29 | 5.49 | 1.44 |
| 9 | Oxidation | 5.58 | 1.38 | 5.94 | 1.31 |
| 10 | Reducing ability | 5.51 | 1.46 | 5.57 | 1.41 |
| 11 | Reduced | 5.49 | 1.37 | 5.49 | 1.45 |
| 12 | Reduction | 5.40 | 1.53 | 5.78 | 1.39 |
| 13 | Oxidized | 5.31 | 1.43 | 5.38 | 1.48 |
| 14 | Oxidation product | 5.20 | 1.32 | 5.31 | 1.50 |
| 15 | Reduction product | 5.04 | 1.45 | 5.28 | 1.54 |
| - | Metallic corrosion | 4.90 | 1.63 | 4.55 | 1.73 |

*The Competing Models of Redox Reaction*

The data of Sample 6a were analyzed with EFA, and then a model with two factors emerged. The value of Bartlett's test of sphericity is 2905.717 ($p < .001$) and the value of the Kaiser-Meyer-Olkin (KMO) measure of sample adequacy is .926 > .70, indicating that the factor analysis is adequate (Mai, Qian, Li et al., 2021). Two factors were retrieved based on the Eigenvalue larger than 1, which together explained 69.862% of the variance.


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As illustrated in Table 4, factor 1 consists of 10 items with factor loadings ranging from .714 to .907, while factor 2 contains 5 items with factor loadings ranging from .532 to .937, indicating that the two factors have good explanatory power for the corresponding items (Oort, 2011).

**Table 4**
*The Model Acquired by EFA*

| Factor | Number of items | Range of loadings | Items | The cumulative variance contribution rate |
|---|---|---|---|---|
| 1 | 10 | .714–.907 | 3, 4, 8, 9, 10, 11, 12, 13, 14, 15 | 58.727 |
| 2 | 5 | .532–.937 | 1, 2, 5 , 6, 7 | 69.862 |

To obtain more competing models, 20 students in Sample 6 were randomly invited to classify the 15 concepts according to their understanding in a paper-pencil test. As a result, six models were recognized. The name and frequency of each model are shown in Table 5. F2 model refers to a model with two factors, which is identical to the model derived from EFA. F3a, F3b, and F3c models are three kinds of models with three factors, which are three different results of splitting factor 1 of the F2 model into two factors. F4a and F4b models are two distinct models with four factors. F4a model was formed by splitting factor 1 of the F3a model into two factors, while the F4b model was formed by splitting factor 1 of the F3b model into two factors. All in all, six initial rival models were prepared for CFA.

**Table 5**
*The Distributions of Concepts in Six Initial Models*

| Model | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Frequency |
|---|---|---|---|---|---|
| F2 | 3, 4, 8, 9, 10, 11, 12, 13, 14, 15 | 1, 2, 5, 6, 7 | - | - | 6 |
| F3a | 4, 8, 9, 11, 12, 13, 14, 15 | 3, 10 | 1, 2, 5, 6, 7 | - | 5 |
| F3b | 3, 4, 8, 10, 14, 15 | 9, 11, 12, 13 | 1, 2, 5, 6, 7 | - | 4 |
| F3c | 3, 4, 9, 13, 14 | 8, 10, 11, 12, 15 | 1, 2, 5, 6, 7 | - | 2 |
| F4a | 4, 8, 14, 15 | 9, 11, 12, 13 | 3, 10 | 1, 2, 5, 6, 7 | 2 |
| F4b | 3, 4, 14 | 8, 10, 15 | 9, 11, 12, 13 | 1, 2, 5, 6, 7 | 1 |

### *The Knowledge Structure of Redox Reaction*

Numerous fit indices are capable of evaluating the model's reliability (Schreiber et al., 2006). However, academics have not established a consensus on which fit index is superior. To avoid misevaluating the models as much as possible, we combined four fit indices as the evaluation criteria: Root Mean Square Error of Approximation (RMSEA) $< .08$, Comparative Fit Index (CFI) $> .90$, Tucker-Lewis Index (TLI) $> .90$ (Kline, 2005), and Standardized Root Mean Square Residual (SRMR) $< .08$ (Hu & Bentler, 1999). As shown in Table 6, the RMSEA, CFI, and TLI of the six initial models are not within the acceptable range of model fit, indicating that the six models do not adequately match the data. The modification index by Mplus suggests adding error covariances between some items. The modified suggestions of both F3a and F4a models are adding error covariances between items "oxidation product" and "reduction product", while the modified suggestions of F2, F3b, F3c, and F4b models are adding error covariances between items "oxidation product" and "reduction product", items "oxidizing ability" and "reducing ability". The specific modified information is shown in Table 6.

Upon further examination, we discovered that two pairs of items that need to be added error covariances are highly correlated in terms of chemical knowledge. First, the oxidation product and reduction product must be produced simultaneously in a redox reaction. Secondly, oxidizing ability and reducing ability refer to the ability of a substance to gain and lose electrons, respectively. Moreover, two error covariances modifications are within-factor. From these aspects, we accepted the suggestions of the software and used CFA to test each modified model.


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Each model was tested once when each corresponding error covariance was added. The fit indices of the six final modified models fit the data well, as shown in Table 7. Chi-square difference tests were conducted between the six initial models and the corresponding modified models (Schreiber et al., 2006), and the associated parameters are listed in Table 8. All *p* values are less than .001, suggesting that the model fit of the modified models is improved significantly compared with the matching initial models (Mai, Qian, Li et al., 2021).

**Table 6**
*The Fit Indices of Initial Models Derived from CFA*

| Model | S-B $\chi^2$ | *df* | RMSEA [90% CI] | CFI | TLI | SRMR | Modification suggestions |
|---|---|---|---|---|---|---|---|
| F2 | 298.589* | 89 | .101 [ .089, .114] | .864 | .840 | .047 | 1, 2 |
| F3a | 267.434* | 87 | .095 [ .082, .108] | .883 | .859 | .045 | 1 |
| F3b | 290.166* | 87 | .101 [ .088, .114] | .868 | .841 | .046 | 1, 2 |
| F3c | 290.285* | 87 | .101 [ .088, .114] | .868 | .841 | .047 | 1, 2 |
| F4a | 252.060* | 84 | .093 [ .080, .107] | .891 | .864 | .045 | 1 |
| F4b | 281.787* | 84 | .101 [ .088, .115] | .872 | .840 | .046 | 1, 2 |

*Note:* *p $<$ .001, modification suggestions "1" and "2" refer to adding error covariances between items "oxidation product" and "reduction product", items "oxidizing ability" and "reducing ability", respectively.

**Table 7**
*The Fit Indices of Modified Models Derived from CFA*

| Model | S-B $\chi^2$ | *df* | RMSEA [90% CI] | CFI | TLI | SRMR |
|---|---|---|---|---|---|---|
| F2-1 | 210.827* | 87 | .079 [ .065, .092] | .920 | .903 | .042 |
| F3a-1 | 210.365* | 86 | .079 [ .066, .093] | .919 | .902 | .042 |
| F3b-1 | 203.567* | 85 | .078 [ .064, .092] | .923 | .905 | .043 |
| F3c-1 | 192.279* | 84 | .075 [ .061, .089] | .930 | .912 | .048 |
| F4a-1 | 202.158* | 83 | .079 [ .065, .093] | .923 | .902 | .043 |
| F4b-1 | 196.364* | 82 | .078 [ .064, .092] | .926 | .905 | .043 |

*Note:* *p $<$ .001

**Table 8**
*The Indices of Chi-square Difference Test*

| Initial model | Modified model | cd | TRd | *p* |
|---|---|---|---|---|
| F2 | F2-1 | 3.326 | 49.046 | $<$ .001 |
| F3a | F3a-1 | 5.225 | 21.013 | |
| F3b | F3b-1 | 3.207 | 49.735 | |
| F3c | F3c-1 | 3.229 | 56.594 | |
| F4a | F4a-1 | 3.883 | 23.625 | |
| F4b | F4b-1 | 3.353 | 47.071 | |

*Note:* "cd" refers to difference test scaling correction, and "TRd" refers to Satorra-Bentler scaled chi-square difference test.


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High correlation coefficients among factors of a model strongly support combining the high-correlation-coefficients factors (Duffin et al., 2012). In general, inter-factor correlations need to be less than .8 to be considered as distinct factors (Brown, 2006). However, experts recommended that we use inter-factor correlations of less than .9 as the criterion because many concepts related to redox reaction are unity of opposites, resulting in strong correlation coefficients among factors.

Table 9 shows the four modified models that include factors with high correlation coefficients. All F3b-1, F3c-1, and F4b-1 models turned into a new model with two factors after integrating the high correlation factors of F3b-1 (factor 1 and factor 2), F3c-1 (factor 1 and factor 2), and F4b-1 models (factor 1, factor 2, and factor 3), respectively. Meanwhile, a new model with three factors was formed after integrating factor 1 and factor 2 of the F4a-1 model. The distributions of concepts in the new model with two factors and the new model with three factors are the same as the F2-1 and F3a-1 models, respectively. Models with the same distribution of concepts will provide the same model after fitting the same data and being modified. Therefore, the new model with two factors evolved into the F2-1 model after modification according to the same rating data, while the new model with three factors turned into the F3a-1 model. In other words, the F3b-1, F3c-1, and F4b-1 models were converted into the F2-1 model after integrating factors with correlations greater than .9 and matching the rating data, while the F4a-1 model was transformed into the F3a-1 model.

In conclusion, the six modified models in Table 7 fit the data well. It shows that these 15 concepts have six organizational forms in students' minds. However, the high inter-factor correlations indicate that the F2-1 and F3a-1 models are more representative. Therefore, F2-1 and F3a-1 models were accepted as students' knowledge structures of redox reaction. The F2-1 model composed of two factors was called two-factor model, while the F3a-1 model comprised of three factors was labeled three-factor model. The structural diagrams of the two models are depicted in Figure 1 and Figure 2, respectively.

**Table 9**
*The High-Correlation-Coefficients Factors of Modified Models*

| Modified model | The high-correlation-coefficients factors | Correlation coefficient | New model | |
|---|---|---|---|---|
| | | | Number of factors | Distribution of concepts |
| F3b-1 | Factor 1 and factor 2 | .951 | 2 | Factor 1: 3, 4, 8, 9, 10, 11, 12, 13, 14, 15<br>Factor 2: 1, 2, 5, 6, 7 |
| F3c-1 | Factor 1 and factor 2 | .994 | | |
| F4b-1 | Factor 1 and factor 2 | .967 | | |
| | Factor 1 and factor 3 | .924 | | |
| | Factor 2 and factor 3 | .958 | | |
| F4a-1 | Factor 1 and factor 2 | .933 | 3 | Factor 1: 4, 8, 9, 11, 12, 13, 14, 15<br>Factor 2: 3, 10<br>Factor 3: 1, 2, 5, 6, 7 |

*Note*: "New model" refers to the model formed due to the changes in the distribution of concepts after merging the highly correlated factors.


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**Figure 1**
*Two-factor Model*

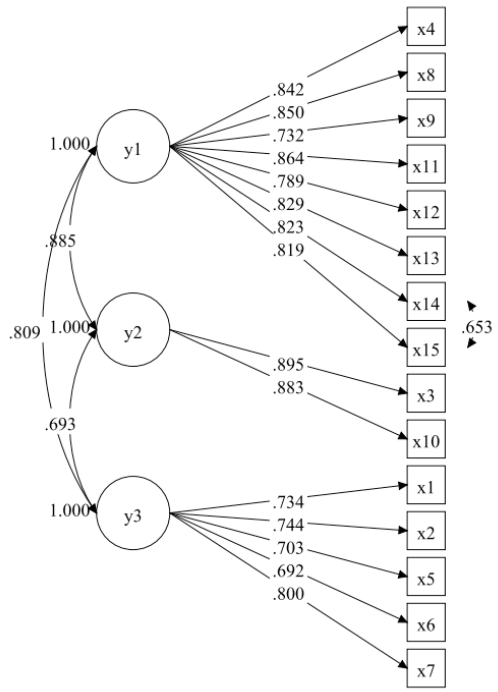
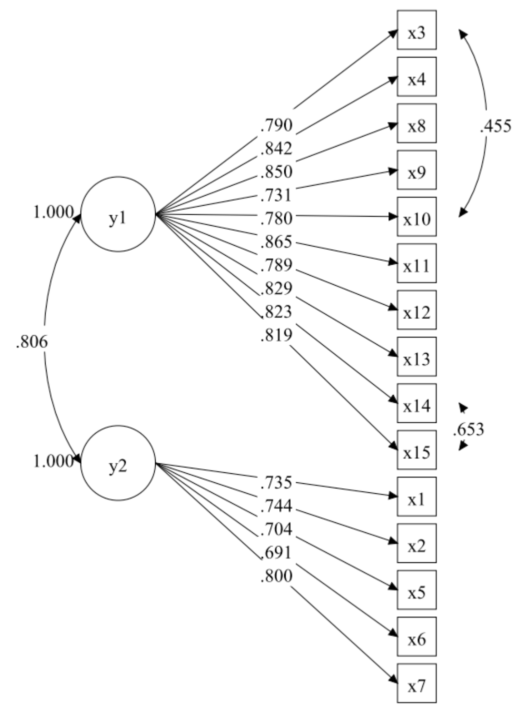



**Figure 2**
*Three-factor Model*




## Discussion

In this study, 15 concepts were selected as the concept pool of redox reaction, and the two- and three-factor models were regarded as the students' knowledge structures of redox reaction by using factor analysis.

*The Concept Pool of Redox Reaction*

Many chemical phenomena and principles involve the knowledge of redox reaction. Therefore, there are many concepts related to redox reaction. However, only highly relevant concepts play a key role in students' scientific understanding of redox reaction. Three rounds of concept screening were carried out to obtain the concepts highly related to redox reaction (the concept pool). In the process, we adopted three research methods, including content analysis, questionnaire survey, and interview. On the other hand, we invited a variety of participants, including 333 upper-secondary school teachers, 36 postgraduate students, 8 college professors, and 459 students in Grade 10. Compared to previous studies on redox reaction (Chiang et al., 2014; Jin et al., 2020), the concept pool identified in this study is more objective, credible, and representative.

In the interview with teachers and college professors, 16 concepts were eliminated for three different reasons. To begin, eight concepts are subordinate to others, it is preferable to remove the subordinate concepts to get a concise concept pool. For instance, both "strong oxidizing agent" and "weak oxidizing agent" are "oxidizing agent", but the latter is more general. Thus, we accepted the concept "oxidizing agent" and rejected the concepts "strong oxidizing agent" and "weak oxidizing agent". For the same reason, the concepts "strong oxidizing ability", "weak oxidizing ability", "strong reducing agent", "weak reducing agent", "strong reducing ability", and "weak reducing ability" were deleted, while the concepts "oxidizing ability", "reducing agent", and "reducing ability" were accepted.

Secondly, although some concepts are connected to redox reaction, they are ineffective at assisting Grade 10 students in comprehending redox reaction. Therefore, six concepts ("combustion", "explosion", "metal activity", "slow oxidation", "gain of oxygen", and "loss of oxygen") were rejected. It is noted that students judge redox reaction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mainly from the perspective of the gain and loss of oxygen in junior high school. However, students realize that this method is one-sided after the in-depth study of redox reaction in upper-secondary school and rarely use this method to analyze redox reaction. For upper-secondary school students, the concepts "gain of oxygen" and "loss of oxygen" are relatively unimportant to understand redox reaction. Accordingly, the concepts "gain of oxygen" and "loss of oxygen" were eliminated.

Thirdly, both concepts "oxidizing" and "oxidizing ability" relate to the matter's ability to acquire electrons, and both "reducing" and "reducing ability" refer to the matter's ability to lose electrons. To avoid conceptual duplication and comply with Chinese upper-secondary school textbooks, the concepts "oxidizing ability" and "reducing ability" were preserved, while the concepts "oxidizing" and "reducing" were abolished.

According to the data in Table 2, the ranges of average scores given by teachers and students for these 15 concepts are 5.04–6.56 and 5.28–6.12, respectively. It shows that both teachers and students consider these concepts closely related to redox reaction. Therefore, the 15 concepts in the concept pool can apply to reveal knowledge structure regarding redox reaction of upper-secondary school students.

*The Knowledge Structure of Redox Reaction*

The six initial competing models with 15 concepts were obtained by EFA and paper-pencil test, which were tested and modified using CFA. As a result, the six modified models fit the data well. It implies that students' understanding of the relationships between these 15 concepts is diverse. However, the high inter-factor correlations indicate that the two- and three-factor models are more representative. Thus, the two- and three-factor models were accepted as the knowledge structures of redox reaction held by students. The combination forms of concepts distinguish the two models. The concepts in factor 1 of the two-factor model were recombined into two more refined factors to generate the three-factor model.

As illustrated in Figure 1, the factor loadings of each item in the two-factor model range from .691 to .865, indicating that these factors have good explanatory power for the items (Ximenez, 2016). Factor 1 of the two-factor model contains ten concepts and was named "the process of redox reaction" by the authors. These concepts are "oxidizing ability", "oxidizing agent", "reducing agent", "oxidation", "reducing ability", "reduced", "reduction", "oxidized", "oxidation product", and "reduction product". The internal relationships of the ten concepts are as follows. Take the following redox reaction (a net ionic equation) as an example:

$$Fe_{(s)} + Cu^{2+}{}_{(aq)} \rightarrow Fe^{2+}{}_{(aq)} + Cu_{(s)}$$

Iron metal (reducing agent) is oxidized to form an iron(II) ion (oxidation product), whereas copper ion (II) (oxidizing agent) is reduced to yield copper metal (reduction product). Iron metal is undergoing oxidation and exhibiting reducing ability while copper ion (II) is undergoing reduction and exhibiting oxidizing ability during the reaction given previously.

Factor 2 of the two-factor model contains five concepts and was named "metrology". These concepts are "conservation of gain and loss electrons", "electron transfer", "number of gain and loss electrons", "oxidation numbers", and "oxidation state changes". The internal relationships of the five concepts are as follows. The essence of redox reaction is electron transfer, which includes the gain and loss of electrons. In the net ionic equation above, electrons transfer from iron metal to copper ion (II), the oxidizing number of iron metal increases due to the loss of electrons, while the oxidizing number of copper ion (II) decreases as the result of the gain of electrons. The number of electrons lost is equal to the number of electrons gained, which comprises the meaning of the concept "conservation of gain and loss electrons".

As demonstrated in Figure 2, the factor loadings of each item in the three-factor model range from .692 to .895, showing that these factors have adequately strong explanatory power for the items. The precise names and implications of the three factors are given as follows.

The name of factor 1 was "the process of redox reaction", including concepts "oxidizing agent", "reducing agent", "oxidation", "reduced", "reduction", "oxidized", "oxidation product", and "reduction product". In a redox reaction, the oxidizing agent is undergoing reduction and reduced to produce the reduction product, while the reducing agent is undergoing oxidation and oxidized to produce oxidation product.

Factor 2 contains two concepts: "oxidizing ability" and "reducing ability". Oxidizing ability and reducing ability refer to the ability of a substance to gain and lose electrons, respectively. Therefore, this factor was named "reaction ability". Factor 3 was called "metrology", and its concepts and meaning are the same as that of factor 2 in the two-factor model.


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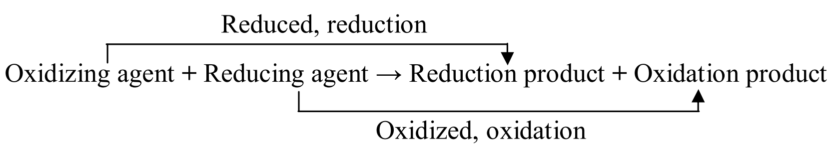
In-depth interviews reveal that although students have the two- and three-factor models, they may not fully understand the meanings of the 15 concepts and the relationships between them. This is reflected in some students' confusion about the meanings of some concepts, such as oxidizing agent and reducing agent, oxidation product and reduction product. On the other hand, some students indicated that the teachers usually guide them to analyze the redox reaction through the model in Figure 3, so they could classify these concepts into one category. In fact, some of them only memorize the model but do not comprehend the scientific connections between the concepts in the model (Yan, 2011). In other words, the model in Figure 3 may be passively accepted rather than actively constructed based on understanding by some students. Based on this, teachers can design corresponding teaching tasks to help students correctly understand the meanings and interrelationships of the concepts.

**Figure 3**

*The Model Summarized by Chinese Upper-Secondary School Chemistry Teachers*




The distributions of concepts in the two- and three-factor models are consistent with the two most frequent models proposed by students in the paper-pencil test. This demonstrates that the models obtained from factor analysis can reflect the knowledge structures in most students' minds. Based on this, it can be concluded that factor analysis can indeed be used to investigate the knowledge structures in the field of science education, particularly in chemistry. Furthermore, the models obtained by factor analysis can provide more detailed information (Herwin & Nurhayati, 2021). For example, according to the error covariances between concepts, we can know which concepts are not only explained by the corresponding factor but also links to each other by unknown variables.

**Conclusions and Implications**

In this study, factor analysis was utilized to investigate the knowledge structure of redox reaction from 459 Grade 10 students. The concept pool of redox reaction contains 15 concepts. The two- and three-factor models serve as the knowledge structures of students in Grade 10. The two-factor model consists of two components: the process of redox reaction and metrology. The three-factor model is composed of three components: the process of redox reaction, reaction ability, and metrology. Overall, this study further confirms that factor analysis is a proper method to reveal knowledge structure regarding a specific learning topic, especially in chemistry.

Some implications are drawn from the preceding conclusions. First, teachers can use 15 concepts in the concept pool to evaluate students' understanding of redox reaction. These concepts are highly related to redox reaction and play a key role in students' understanding. Through in-depth interviews, we found that some students may not fully grasp the meanings and relationships of these concepts. Therefore, teachers can design corresponding identification tasks for these 15 concepts to assess students' comprehension. Then, teachers can conduct interviews with students to find out the reasons for students' misunderstanding. Based on the results of the above two sections, teachers can design appropriate teaching tasks to correct or deepen students' understanding of redox reaction, and then assist students in developing more diverse, flexible, and scientific knowledge structures of redox reaction.

Second, further research can be conducted to determine the association between different knowledge structures regarding redox reaction and the academic achievement of students. This study found that students' knowledge structures of redox reaction are diverse. However, the relationship between students' academic achievement and their knowledge structures is unknown. We predict that students with different levels of academic achievement may have different knowledge structures. Therefore, it is necessary to explore the differences in the knowledge structures of students with high and low academic achievement levels. The results can provide a reference for teachers to effectively carry out hierarchical teaching designs for students with different academic performances.

Third, it is appropriate to concentrate on the development of students' knowledge structures of redox reaction. Students' understanding of redox reaction will continue to develop with the learning of new knowledge, which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may have an impact on students' knowledge structures. Therefore, subsequent researchers can investigate the knowledge structures regarding redox reaction of upper-secondary school freshmen, sophomores, and juniors, to provide support for teachers to adopt targeted teaching in each learning stage.

**Declaration of Interest**

The authors declare no competing interest.

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