Study on the Combustibility of Main Tree Species in Mu Us Sandy Land

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Abstract: The physical and chemical properties of fuels determine forest combustibility, influence forest fire intensity, spread speed and so on. The physical and chemical properties of fuels are influenced by the moisture, ash and calorific of combustibles. It is important to study the combustibility of main arbor in forest for reducing the intensity of forest fire and protecting forest resources. The moisture, calorific, ignition temperature, crude fat and ash of 21 major Mu Us Sandy land species were measured and analyzed, principal component analysis (PCA) was used to comprehensively rank the physical and chemical properties of arbor and shrub. The results can provide scientific basis for the fire resistance of arbor structure in the Mu Us Sandy land, prevent and reduce the frequency of fire in the region, and protect the ecological resources in the sandy land.

Keywords: Mu Us Sandy Land; principal component analysis; flammability; fire resistance.

1. Introduction
Forest fires are devastating to balance of nature and natural resources. With the global warming, the increase of the average temperature in China, the frequent occurrence of drought and other natural disasters, the forest fire risk index has increased obviously, and the fire frequency and the fire area have an upward trend [1]. The combustibility of forest fuel plays a decisive role in the occurrence and spread of fire, and the judgement of combustibility should refer to many physical and chemical properties, including moisture content, calorific value, crude fat, ignition temperature and so on[2-3]. The study on combustibility of combustibles can provide scientific basis for predicting forest fire danger and optimizing forest structure. Many researches have been done on forest combustibility by using the physical and chemical properties of combustibility. Wang Lei[4] et al used principal component analysis (PCA) to study the combustibility of 21 main garden arbor in Hohhot, and to screen city fire-resistant arbor. Li Ke [5] studied the heat release rate, the peak value of heat release rate, the effective combustibility, the total heat release, the ignition time and the mass loss rate of five arbor in Nanjing, the order of combustibility from strong to weak was Pinus massoniana, Cunninghamia lanceolata, Platycladus orientalis, Quercus acutissima and ligustrum lucidum. Based on the time delay equilibrium moisture content method, the moisture content prediction model of dead fuel on the ground surface of key forest types in Greater Khingan was established. Liang Ying[7] et al measured the calorific value, ash
content, moisture content and extracts of nine main arbor in the central forest region of Ten-zan, and evaluated the combustibility of the arbor by using multivariate statistical methods and a comprehensive evaluation system of Flammability Index [8]. principal component analysis (PCA) was used to analyze the combustibility of surface fuel under five main forest types in Greater Khingan, the results show that the order of combustibility of surface layer is quercus mongolica, betula platyphylla, Betula dahurica, Larix gmelinii and Populus davidiana. In the 1860s, Bram [9] began to study the combustibility of forest fuel. Wilgen [10] evaluated the combustibility of South African arbor by biomass, leaf moisture content, caloric value and crude fat, Chnadle [11] measured the moisture content of broad-leaved forest and shrubbery. The results showed that the moisture content of leaves was the highest in spring and the fire resistance was strong. Therefore, it is feasible to evaluate the combustibility of arbor based on the comprehensive evaluation of the combustibility.

Mu us sandy land is arid climate, perennial wind speed is large, fire often occurs. So taking the representative tree and shrub species of Mu Us Sandyland as the research object, the physical and chemical characteristics of each arbor were tested, the combustibility of the arbor was comprehensively ranked by principal component analysis, and the fire resistant arbor were selected, the results are important for maintaining the ecosystem balance of the Mu Us Sandyland, preventing forest fires and reducing the risk of forest fires.

2. Materials and methods

2.1. Survey of the study area
The Mu Us Sandyland is located at the Ordos City of Yulin and Inner Mongolia, with an area of 4.22 × 10³ km². Latitude 37° 27.5′ ~39° 22.5′, longitude 107° 20′ ~111° 30′, is one of the four major sandy land in China. Annual precipitation of 250mm~440mm, mostly concentrated in july-september, accounting for 60%~75% of the annual precipitation. The interannual variation rate of precipitation is large, drought and waterlogging often occur, drought is more than waterlogging, frequent drought leads to drier vegetation in sandy land, and strong wind often passes through sandy land, vegetation moisture content decreases under the effect of temperature and wind speed, and combustibility increases.

2.2. Experimental arbor and shrub
The experimental arbor of Mu Us Sandyland mainly include arbors and shrubs, arbor: Picea asperata Mast, Pinus sylvestris var. mongolica Litv, Platycladus orientalis (L.) Franco, Pinus tabuliformis Carriere, Populus × hopeiensis Hu & Chow, Armeniaca vulgaris Lam., Populus opera Hsii, shrub species: Sabina vulgaris Antoine, Salix cheilophila, Caragana korshinskii, Prunus discadenia, Hedysarum scoparium, Artemisia desertorum Spreng., Hedysarum laeve Maxim, Amorpha fruticosa L., Cornus alba Linnaeus, Ligustrum obtusifolium Sieb. et Zucc, Hippophae rhamnoides L.

2.3. Experimental method
The samples of experimental arbor collected in the field were marked in an envelope bag and their fresh weight was stated. The samples were taken back to the laboratory, placed in an oven at (102 ± 3) °C and dried until the quality was constant. The samples were taken out and crushed and screened over 300 mesh, keep small sample powder in the drying box for moisture content, calorific value, ignition temperature, ash, crude fat index determination.

2.3.1. Determination of moisture content of combustibles. The relative moisture content was calculated by weighing the sample with electronic balance after the sample was dried continuously at 105 °C for 24 hours to a constant dry weight. The formula is as follows:

\[ \text{AMC} = \frac{(WH - WD)}{WD} \times 100\% \] (1)
In the formula, AMC is the relative moisture content, $W_H$ is the wet weight and $W_D$ is the dry weight of fuel.

2.3.2. *Determination of calorific value of combustibles.* After the powder is pressed, the calorific value of combustible is measured by XRY-1C microcomputer oxygen bomb calorimeter.

2.3.3. *Determination of ignition temperature of combustibles.* After the ZY6069 reaches the set-up temperature, the 2g~3g sample is put into the sample holder, and the lowest temperature is the combustible ignition temperature after the continuous flame of more than 5s appears after repeated tests.

2.3.4. *Determination of ash in combustibles.* The sample powder of 1g ~ 2g was dried and burned at 650 °C for 6-8 hours in a box-type resistance furnace.

2.3.5. *Determination of crude fat of combustibles.* The filter paper was wrapped with 1g ~ 2g sample powder and put into oil extraction bottle. After drying, the sample crude fat was determined by SZF-06 crude fat analyzer.

2.3.6. *Principal component analysis.* Principal Component Analysis (PCA) is an Analysis method which transforms data from multi-dimension to low-dimension variables. The evaluation of combustibility of arbor should be carried out through comprehensive calculation of several indexes, so the principal component analysis is used to eliminate excessive overlapping information, and the contribution degree of each combustibility index is comprehensively evaluated, and the arbor combustibility is ranked according to the comprehensive score, can accurately reflect the true situation of the combustibility of arbor [12].

The steps for comprehensive evaluation using principal component analysis are as follows:

Step 1: standardize the raw data and eliminate the influence of variables on the dimension.

Step 2: determine the number of principal components according to the accumulative contribution rate of principal components, and select the eigenvalue > 1 as the principal component.

Step 3: to further explain the actual meaning of each principal component, the original factors are rotated by the choice of maximum variance to explain each principal component. According to the factor score, the principal component score is calculated by Formula (2):

$$F_i = b_i * X_i \quad (i=1,2,3...)$$  \hspace{1cm} (2)

In the formula, $F_i$ is the principal component scores, $b_i$ is the factor scores, and $X$ is the arithmetic square root of the eigenvalues of each principal component.

Step 4: according to the principal component score, using formula (3) to calculate the combusting comprehensive score of different arbor:

$$F_z = \sum_{i=1}^{m} \left( \frac{\lambda_i}{\sum \lambda_i} \right) F_i \quad (i = 1,2,3 ...)$$  \hspace{1cm} (3)

In the formula, $F_z$ is the arbor combustion comprehensive score, $F_i$ is the principal component score, $\lambda_i$ is the first principal component corresponding to the eigenvalue.

2.4. *Data processing and analysis*

Using Origin2019b to classify the combustible physical and chemical properties, drawing the physical and chemical properties chart, using SPSS 25 to analyze the principal component, calculate the combusting comprehensive score.
3. Results and analysis

3.1. Analysis of physical and chemical properties of Mu Us Sandyland vegetation

3.1.1. Moisture content. As shown in Figure 1, the water content of 21 tree and shrub species in Mu Us Sandyland is mostly 54%~65%, the average is 62%, the water content of shrub species is 30%~52%, the average is 43%, generally, the water content of arbor is higher than that of shrub species. The highest water content of Picea asperata is 85%, the highest water content of Hippophae rhamnoides is 58%, the difference of the highest water content between two species is 30%.

![Figure 1. Moisture content](image1.png)

Note: X1: Salix alba var. pyramidalis Bunge, X2: Populus × hopeiensis Hu & Chow, X3: Armeniaca vulgaris Lam, X4: Populus opera Hsii, X5: Rhus typhina, X6: Robinia pseudoacacia L, X7: Pinus sylvestris var. mongolica Litv, X8: Pinus tabuliformis Carriere, X9: Picea asperata Mast, X10: Platyclus orientalis (L.) Franco, X11: Caragana korshinskii, X12: Amorpha fruticosa L, X13: Hippophae rhamnoides L, X14: Prunus discadenia, X15: Salix cheliophila, X16: Hedysarum laeve Maxim, X17: Hedysarum scoparium, X18: Cornus alba Linnaeus, X19: Ligustrum obtusifolium Sieb. et Zucc, X20: Artemisia desertorum Spreng, X21: Sabina vulgaris Antoine, the same below

3.1.2. Caloric value. The caloric values of arbor and shrub species are as shown in Figure 2. The caloric values of arbor and shrub species are mainly distributed in 19800 J·kg\(^{-1}\)~21100 J·kg\(^{-1}\) and 19450 J·kg\(^{-1}\)~20900 J·kg\(^{-1}\). The mean values are 20600 J·kg\(^{-1}\) and 20200 J·kg\(^{-1}\), respectively. The caloric values of arbor and shrub species are slightly higher than that of shrub species, the gap is smaller. The caloric value of Pinus tabuliformis Carriere was 22517 J·kg\(^{-1}\). The caloric value of Prunus discadenia and Sabina vulgaris Antoine were 21212 J·kg\(^{-1}\) and 21061 J·kg\(^{-1}\), respectively. The calorific value is equivalent to Pinus tabuliformis Carriere and the combustion property is strong.

![Figure 2. Calorific values](image2.png)
3.1.3. Ignition temperature. As shown in fig 3, the ignition temperatures of tree and shrub species are 261 °C~274 °C and 265 °C ~275 °C, respectively. The mean fire temperatures are similar, about 268°C. The differences of fire temperatures between tree and shrub species are small, and the ignition temperatures of shrub species are generally larger than that of arbor, among them, Populus opera Hsii, Rhus typhina, Salix cheilophila, Hedysarum laeve Maxim, Sabina vulgaris Antoine and other arbor and shrub species ignition temperature is higher, about 270 °C.

![Figure 3. Ignition temperature](image)

3.1.4. ash. The ash contents of tree and shrub species are 2.2% ~4.1% and 1.3% ~2.3% , respectively. The average ash contents of shrub species were 3.2% and 1.6% , respectively. The ash contents of arbor are 50% lower than those of arbor. The ash contents of arbor are higher than those of Pinus sylvestris var. mongolica Litv and Picea asperata Mast, the ash content of Sabina vulgaris Antoine is the highest, about 3%. The ash value is shown in fig 4.

![Figure 4. Ash content](image)

3.1.5. Crude fat content. The crude fat content of arbor and shrub species is shown in fig 5, 4.5%~12% and 4.4%~6% respectively, with the mean values of 8.5% and 7%, respectively. The crude fat content of shrub species varies greatly, and the shrub species is generally lower than the arbor. However, the crude fat content of two shrubs, Sabina vulgaris Antoine and Hippophae rhamnoides L, reached 17.8% and 16.4%, respectively, which was higher than that of Pinus tabuliformis Carriere.
3.2. Order of comprehensive flammability score

Using SPSS 25 software, the physical and chemical properties of arbor and shrub species were analyzed by principal component analysis, and the combustibility of arbor and shrub species were compared according to the order of comprehensive scores.

The characteristic values and variance contribution rates of principal component analysis for arbor and shrub species are shown in tables 1. The number of principal components was selected according to the principle of eigenvalue > 1. As shown in Table 1, two principal components were extracted. The eigenvalues were 2.688 and 1.158 respectively. The cumulative variance contribution of the two principal components was 76.929%, representing the combustibility information of arbor 76.929%, the principal component analysis of shrub species in table 2 showed that the characteristic values were 2.126 and 1.374, and the contribution of variance was 70.004%.

Table 1. Eigenvalue and contribution rate of arbor and shrub

| Variables         | Arbor          | Shrub          |
|-------------------|----------------|----------------|
|                   | Eigenvalues    | Variance       | Cumulative     | Eigenvalues    | Variance       | Cumulative     |
|                   | Contribution  | contribution   | variance       | Contribution  | contribution   | variance       |
|                   | (%)           | (%)            | (%)            | (%)           | (%)            | (%)            |
| 1                 | 2.688         | 53.770         | 53.770         | 2.126         | 42.519         | 42.519         |
| 2                 | 1.158         | 23.159         | 76.929         | 1.374         | 27.485         | 70.004         |

The orthogonal rotation of the principal component load matrix of arbor and shrub is shown in tables 2. The orthogonal rotation matrix represents the degree of influence of each variable on each principal component, the principal component 1 in table 2 is composed of calorific value, crude fat and moisture content. The principal component 2 has the highest ash coefficient, which can be regarded as the ash content index of the tree. In table 2, the principal component 1 of shrub vegetation is mainly composed of crude fat and ash, and the principal component 2 mainly reflects the calorific value index information of shrub species.

Table 2. Each index load matrix of arbor and shrub rotates orthogonally

| Variables         | Arbor          | Shrub          |
|-------------------|----------------|----------------|
|                   | Principal Component 1 | Principal Component 2 | Variables         | Principal Component 1 | Principal Component 2 |
| Moisture content  | 0.731          | 0.526          | Moisture content  | -0.567         | 0.621          |
| Calorific values | 0.838          | -0.399         | Calorific values | -0.030         | 0.816          |
| Ignition temperature | -0.662        | 0.250          | Ignition temperature | 0.562        | -0.331         |
| Ash content       | 0.575          | 0.725          | Ash content       | 0.876          | 0.361          |
| Crude fat content | 0.826          | -0.365         | Crude fat content | 0.849          | 0.290          |
The factor scores of each tree species are shown in table 3. The comprehensive burning scores and ranking results of each tree species are calculated by substituting the factor scores of each tree species and the principal component characteristic values into Equation (3).

| Arbor | Shrub |
|-------|-------|
| Species | Principal component 1 | Principal component 2 | Species | Principal component 1 | Principal component 2 |
| X1    | -0.76185 | 0.04973 | X11   | -0.13454 | 0.45310 |
| X2    | -0.25265 | -0.45013 | X12   | 0.26700  | -1.36801 |
| X3    | -0.30026 | -0.44208 | X13   | -1.44453 | 0.00413 |
| X4    | -0.98890 | 1.08530  | X14   | -0.61523 | 0.99300 |
| X5    | 0.94479  | 0.02123  | X15   | 1.62102  | -0.82566 |
| X6    | -1.06251 | 0.10742  | X16   | 0.42658  | -0.82658 |
| X7    | 0.91825  | 1.21036  | X17   | 0.55614  | -0.86022 |
| X8    | 0.64056  | -2.21436 | X18   | -0.81821 | 0.18685 |
| X9    | 1.71181  | 0.96481  | X19   | -0.91759 | -0.40730 |
| X10   | 1.04034  | -0.33228 | X20   | -0.53191 | 0.57756 |
| X21   | 1.59126  | 2.07313  | X21   | 1.59126  | 2.07313  |

The comprehensive indexes of combustibility of arbor and shrub species are listed in table 4, the order of combustibility of arbor from strong to weak is: *Picea asperata* Mast, *Pinus sylvestris var. mongolica* Litv, *Platycladus orientalis* (L.) Franco, *Pinus tabuliformis* Carriere, *Populus × hopeiensis Hu & Chow*, *Armeniaca vulgaris* Lam, *Populus opera* Hsii, *Salix alba var. pyramidalis* Bunge, *Rhus typhina*, *Robinia pseudoacacia* L. The order of shrub species from strong to weak is: *Sabina vulgaris* Antoine, *Salix cheilophila*, *Caragana korshinskii*, *Prunus discadenia*, *Hedysarum scoparium*, *Artemisia desertorum* Spreng, *Hedysarum laeve* Maxim, *Amorpha fruticosa* L., *Cornus alba* Linnaeus, *Ligustrum obtusifolium* Sieb. et Zucc, *Hippophae rhamnoides* L.

| Arbor | Shrub |
|-------|-------|
| Species | Comprehensive scores | Rank | Species | Comprehensive scores | Rank |
| X9    | 2.150612075 | 1 | X21   | 10.41756567 | 1 |
| X7    | 1.430179236 | 2 | X15   | 3.655863558 | 2 |
| X10   | 0.940332845 | 3 | X11   | 0.607292303 | 3 |
| X8    | -0.223242288 | 4 | X14   | 0.221945687 | 4 |
| X2    | -0.440248932 | 5 | X17   | -0.112044286 | 5 |
| X3    | -0.481387999 | 6 | X20   | -0.473460001 | 6 |
| X4    | -0.587016166 | 7 | X16   | -0.480850226 | 7 |
| X1    | -0.765892525 | 8 | X12   | -2.315411295 | 8 |
| X4    | -0.965945992 | 9 | X18   | -2.389735561 | 9 |
| X6    | -1.052954004 | 10 | X19  | -4.140763177 | 10 |
| X13   | -4.990437286 | 11 | X13  | -4.990437286 | 11 |
4. Conclusion

The physical and chemical properties of forest combustibility have an important influence on forest combustibility and play a decisive role in the occurrence and spread of forest fires. Principal component analysis (PCA) was used to evaluate the combustibility of main arbor in forest land, and the results provided scientific basis for the selection of fire-resistant arbor in Mu Us Sandyland. The results are as follows:

(1) The average water content of tree and shrub species were 62% and 43% respectively, the average water content of arbor was higher than that of shrub was 44%, the average calorific value of arbor and shrub species were 20600 J·kg\(^{-1}\) and 20200 J·kg\(^{-1}\) respectively, and the mean Ignition temperature of arbor was similar to that of shrub, about 268 °C, the average value of the Ignition of arbor and shrub was smaller, but the Ignition of shrub was mainly 265 °C~275 °C, which was larger than that of arbor. The average value of ash content of arbor and shrub was 3.2% and 1.6% respectively, the ash content of shrub was 50% lower than that of arbor species, the mean value of crude fat of arbor and shrub species were 8.5% and 7% respectively, and that of shrub species was 17%, but the crude fat content of shrub species of \textit{Sabina vulgaris Antoine} and \textit{Hippophae rhamnoides L} was 17.8% and 16.4% respectively, the crude fat content of \textit{Pinus tabuliformis Carriere} was higher than that of arbor.

(2) The main indexes of comprehensive calculation of the combustibility of arbor were calorific value, crude fat, moisture content and ash content, while those of shrub were mainly composed of crude fat, ash content and calorific value, the index of water content of shrubs was less than that of arbor in the evaluation of combustibility, the order of combustibility of arbor from big to small was: \textit{Picea asperata} Mast, \textit{Pinus sylvestris} var. mongolica Litv, \textit{Platycladus orientalis} (L.) Franco, \textit{Pinus tabuliformis Carriere}, \textit{Populus × hopeiensis Hu & Chow}, \textit{Armeniaca vulgaris Lam}, \textit{Populus opera Hsii}, \textit{Salix alba} var. pyramidalis Bunge, \textit{Rhus typhina}, \textit{Robinia pseudoacacia L}, the order of combustibility of shrub species were \textit{Sabina vulgaris Antoine}, \textit{Salix cheilophila}, \textit{Caragana korshinskii}, \textit{Prunus discadenia}, \textit{Hedysarum scoparium}, \textit{Artemisia desertorum Spreng}, \textit{Hedysarum laeve Maxim}, \textit{Amorpha fruticosa L}, \textit{Cornus alba} Linnaeus, \textit{Ligustrum obtusifolium Sieb. et Zucc}, \textit{Hippophae rhamnoides L}.

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