Research Article

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Optimization of biochar preparation process and carbon sequestration effect of pruned wolfberry branches

Abstract: Pruned wolfberry branches are abundant and ideal raw material for biomass carbonization. It would provide valuable guidance for optimizing the preparation conditions of biochar of pruned wolfberry branches for carbon sequestration and emission reduction. This study adopted a single-factor experiment and response surface method (RSM) using reaction temperature and holding time as factors, and systematically investigated the effects of carbonization conditions on yield and fixed carbon content. Based on the results, the effects of temperature on yield and fixed carbon content were greater than those of holding time. Both temperature and holding time had extremely significant effects on yield, and the interaction had significant effects. Temperature had an extremely significant effect on fixed carbon content, while holding time and the interaction had no significant effect. Through the RSM, the optimized pyrolysis temperature was 530°C and the holding time was 2 h. The potential for carbonization of biochar generated by wolfberry branches and returned to the soil was evaluated. Biochar was believed to contribute to carbon sequestration and emission reduction in Qinghai province; 68.56 × 10^3 t of carbon emissions could be reduced annually from combustion in the atmosphere and 34.42 × 10^3 t of carbon could be fixed if all biochar were applied to soil.

Keywords: biochar, preparation, carbon sequestration

1 Introduction

As a result of population growth and higher living requirements, the global demand for food is growing exponentially, bringing in more cultivated land. The expansion of production leads to the production of more agricultural waste, often without an appropriate destination. Although many researchers have been devoted to the integration of agricultural production and waste management practices worldwide, the global utilization rate of agricultural waste is only about 30% (or even less) [1]. Biochar is the carbon-rich solid fraction obtained by thermal decomposition of biomass in the presence of limited oxygen reserves [2]. Due to its stable structure, large specific surface area and volume of pores and abundant active functional groups [3], biochar provides broad application perspectives in the areas of environmental remediation [4,5] and soil improvement [6–8], which represents a win–win scenario for achieving more sustainably managed agroecosystems [9]. The preparation of biochar from agricultural waste as raw materials can lead to sustainable processes and low costs, making it an environmentally friendly option [10].

By optimizing the biochar preparation process, the conditions for preparing biochar can be softened and have ideal physical–chemical properties, thus improving biochar performance. In the thermal decomposition process of biomass, the important factors that can be most easily controlled are temperature and holding time [11,12], both of which considerably influence the quality and yield of the final product [13]. Zhao et al. [14] explored the effect of pyrolysis conditions on the preparation of biochar from rape straw and found that pyrolysis temperature and holding time had an impact on the specific surface area, pH, surface functional groups and other properties of biochar. Lu et al. [15] found that the degree of aromatization and stability of biochar increased as the pyrolysis temperature and holding time increased. Previous study has shown that yield, total nitrogen, H:C, and O:C decreased steadily with increasing pyrolysis temperature, while fixed carbon,
C:N, total P, and total K increased consistently with increasing pyrolysis temperature [16]. Improving the yield and quality of biochar by optimizing the preparation conditions is of significant importance and application value.

Soil carbon is the largest carbon pool in the terrestrial biosphere and its sequestration is a key element of global climate modulations [17]. However, when forests or grasslands are converted to agricultural land, the soil organic carbon (SOC) content declines by 30–80% [18,19]. Agriculture, as the basic industry of China’s national economy, accounts for 12–17% of the country’s total greenhouse gas emissions, has great potential for carbon sequestration and emission reduction, and carbon sequestration in soil could account for 90% of agricultural potential [20]. Biochar contains approximately 60% carbon [21], has good resistance to oxidation and degradation, and can be stored stably in soil for thousands of years, removing CO₂ from the atmospheric carbon cycle [22]. The carbon sequestration effect of biochar is determined by its stability. Biochar is highly carbonized and consists mainly of aromatic ring structure and alkyl component, which determines that it has higher chemical stability, thermal stability, and biological stability than other sources of carbon [23]. Kuzyakov et al. [24] showed that the average residency time for biochar was approximately 2,000 years, with a half-life of approximately 1,400 years. The amount of CO₂ generated by biochar mineralization degradation in the culture process is very low, indicating the positive role of biochar in carbon sequestration and emission reduction. In addition, biochar applications can reduce the net potential of global warming by supporting plant growth and absorbing more SOC, thereby reducing the impact of agricultural production on climate change [25]. Biochar technology is estimated to reduce global carbon emissions by about 1 Gt a⁻¹ within 2,050 years [26].

Wolfberry (Lycium barbarum L.) is a perennial deciduous shrub with high medicinal value in fruit and root bark. Qinghai province, located in the northwestern of China, has become an important base for wolfberry cultivation due to its unique climatic conditions and superior natural environment. The area planted with wolfberry increased from 29,950 ha in 2015 to 33,960 ha in 2019, an increase of 11.8% [27]. A large number of branches are obtained from pruning of wolfberry bushes, and most are burned on the spot, which became an important emission source of atmospheric trace components in Qinghai province. The conversion of wolfberry branches into biochar can not only reduce the direct CO₂ emission caused by combustion, but also enhance the effect of soil fertilizer cultivation and carbon sequestration. At present, most biochar is prepared with crop straw as raw material, and wolfberry branches as feeding material for process optimization of derived biochar remain untouched and information in this regard is very much limited. Compared with crop straw, pruned branches have less ash and volatile content, which is beneficial for obtaining high-quality biochar.

In this study, pruned wolfberry branches were used as raw material, taking reaction temperature and holding time as experimental factors, and biochar carbonization conditions suitable for soil carbon sequestration and emission reduction in farmland were determined. The carbon sequestration potential of biochar preparation of wolfberry branches in Qinghai province was analyzed on the basis of planting situation and relevant literature. These results can provide a theoretical basis and technical support for the process control and product quality regulation of the thermal decomposition of pruned wolfberry branches and have certain reference significance for resource reuse and carbon sequestration in Qinghai province.

### 2 Materials and methods

#### 2.1 Materials

The pruned wolfberry branches used in this experiment were obtained from Xiangride Farm (97°80'E, 36°07'N) in Qinghai province, China. The properties of wolfberry branches are presented in Table 1.

#### 2.2 Preparation of biochar

Biochar was produced in a muffle furnace (FO810C, manufactured by Yamta Company). Feeding materials were

| Table 1: Properties of the pruned wolfberry branches |
|-----------------------------------------------|
| **Proximate analysis (%)** | **Composition analysis (%)** |
| Moisture | Volatile matter | Ash | Fixed carbon content | Cellulose | Hemicellulose | Lignin |
| 4.6 | 79.0 | 3.13 | 17.9 | 34.2 | 21.5 | 26.5 |
cut in the size of 10–12 cm and dried in sunlight to reduce moisture content prior to biochar preparation. The dried pruning materials were properly positioned in a crucible. The reactor filled with feeding material was placed inside the furnace. During the whole process of the experiment, an inert gas (N\textsubscript{2}) was used to purge the reactor, and this flow was maintained for approximately 5 min to remove air in the reactor before the test. The inert gas flow rate was maintained at about 5 L\text{min}^{-1}. The prepared biochar was collected after cooling at normal temperature, removed from the reactor, crushed and passed through a sieve <0.15 mm for further analysis. For each condition, experiments were performed three times to confirm reproducibility.

### 2.3 Analytical methods

#### 2.3.1 Biochar preparation and property analysis

The raw materials used for this experiment and the derived biochar were analyzed for several parameters. The yield of prepared biochar (\(\eta\)) was calculated by the following equation:

\[
\eta(\%) = \left(\frac{W_{\text{biochar}}}{W_{\text{feeding material}}}\right) \times 100\% \quad (1)
\]

where \(W_{\text{biochar}}\) and \(W_{\text{feeding material}}\) are the dry weight (g) of the biochar and feeding materials, respectively.

Proximate analysis of feed materials and biochar was performed in accordance with GB T212-2008 for the analysis of moisture content, volatile matter, and ash. Fixed carbon content was calculated by the following equation:

\[
\text{Fixed carbon content (\%)} = 1 - C_{\text{volatile matter}}(\%) - C_{\text{ash}}(\%) \quad (2)
\]

where \(C_{\text{volatile matter}}\) and \(C_{\text{ash}}\) are the volatile content and ash content of biochar or raw materials, respectively.

#### 2.3.2 Carbon sequestration potential calculation

The CO\textsubscript{2} and CO emissions from the burning of wolfberry branches were calculated by the following equation:

\[
E_{\text{CO}_2/\text{CO}}(t) = M(t) \times F_{\text{CO}_2/\text{CO}}(\text{g.kg}^{-1}) \quad (3)
\]

where \(E_{\text{CO}_2/\text{CO}}\) is the emission of CO\textsubscript{2} or CO, \(M\) is the burning quantity of branches, and \(F_{\text{CO}_2/\text{CO}}\) is the emission factor of CO\textsubscript{2} or CO.

Carbon emissions in the combustion process were primarily in the form of CO\textsubscript{2} and CO; therefore, other forms of carbon emissions were ignored in this study. The amount of CO\textsubscript{2} and CO released by combustion was used to estimate the total carbon emission in this region:

\[
CE(t) = 0.27E_{\text{CO}_2}(t) + 0.43E_{\text{CO}}(t) \quad (4)
\]

where \(CE\) is the total carbon release; \(E_{\text{CO}_2}\) and \(E_{\text{CO}}\) are the amount of CO\textsubscript{2} and CO produced by the combustion of branches; 0.27 and 0.43 are the proportion of carbon in CO\textsubscript{2} and CO, respectively.

The calculation formula of carbon fixation (CF) applied by biochar to soil was as follows:

\[
CF(t) = Y(t) \times \eta(\%) \times 80\% \quad (5)
\]

where \(Y\) is the yield of abandoned wolfberry branches; 80\% is the biochar stable fraction ratio.

### 2.4 Statistical analysis

One-way analysis of variance (ANOVA) followed by a pair comparison using the Duncan test was conducted to determine statistically significant differences among several properties. To verify the overall significant difference among the treatments, multivariate ANOVA was also applied. All statistical analyses were performed using IBM SPSS Statistics 26.0 and Design Expert 11; origin 2019 software was used to draw figures.

### 3 Results and discussion

#### 3.1 Single-factor experiment

##### 3.1.1 Effect of temperature on yield and fixed carbon content

The feedstock was heated from normal temperature to seven final sample temperatures (300°C, 350°C, 400°C, 450°C, 500°C, 550°C, and 600°C) separately at a heating rate of 30°C.min\textsuperscript{-1} with retaining 2 h. The effect of temperature on the yield and fixed carbon content of biochar is shown in Figure 1.

It was observed that the yield decreased significantly (\(P < 0.05\)) with temperature rise, consistent with previous studies [28]. The biochar yield decreased by 15.2\% at temperatures ranging from 300°C to 500°C, whereas at temperatures ranging from 500°C to 600°C, it decreased by only 3.0\%. Yield has been shown to be mainly related to the cellulose hemicellulose and lignin content, and different components have different pyrolysis temperatures [29]. At lower pyrolysis temperatures, cellulose
Figure 1: Effect of temperature on yield and fixed carbon content of biochar. Bar plots and points are indicated as mean of three replicates and vertical bar indicates ± SE. Different letters indicate significant differences between treatments at $P < 0.05$.

Based on the analysis of environmental benefits, biochar with more fixed carbon plays an important role in reducing carbon emissions and carbon input into the soil. The fixed carbon content increased with the increase of temperature, and there was no significant difference between 550°C and 600°C, while higher temperature would lead to a further decrease of yield. Therefore, an appropriate temperature for the carbonization of pruned wolfberry branches to produce biochar is 550°C.

### 3.1.2 Effect of holding time on yield and fixed carbon content

At a heating rate of 30°C·min$^{-1}$, the feed material was heated to 500°C and held isothermally for 1, 2, 3, 4, 5, and 6 h. The effect of holding time on the yield and fixed carbon content of biochar is shown in Figure 2.

The yield of biochar was also decreasing with the increase of holding time due to ongoing carbonization reactions. This can be attributed to the fact that as the holding time increased, more organic matter was converted into ash and an amorphous form of carbon (CO$_2$) [37]. The effect of holding time on the fixed carbon content was significant (increased 4.1%) over the 1–2 h range. As the holding time increased, the fixed carbon content also increased. When the retention time was greater than 2 h, the pyrolysis reaction was completed, and the fixed carbon content changed slightly. It was mainly because the longer holding time could promote the internal carbonization of biomass, accelerated the full pyrolysis of lignin, which was difficult to be pyrolyzed, and improved the degree of carbonization.

Figure 2: Effect of holding time on yield and fixed carbon content of biochar. Bar plots and points are indicated as mean of three replicates and vertical bar indicates ± SE. Different letters indicate significant differences between treatments at $P < 0.05$. 

and hemicellulose were decomposed and raw materials were partially burned [30], resulting in higher yield. Lignin was primarily decomposed at high temperature and may lead to increased gasification [31,32], resulting in a declining yield trend. With the increase in pyrolysis temperature, the pyrolysis of raw materials tended to be complete [33,34], so that the change in yield was gradually stable and gentle.

Fixed carbon content is an important criterion for the characterization of biochar and also reflects its stability in soil. In this study, the trend in fixed carbon content was opposite to that of yield. When the pyrolysis temperature was extended from 300°C to 550°C, the fixed carbon content increased significantly ($P < 0.05$), from 56.5% to 82.0%. When the temperature increased from 550°C to 600°C, the fixed carbon content increased from 82.0% to 82.1%, which was almost negligible. The biomass was gradually decomposed, and a series of depolymerization, dehydration, and fracture reactions of C–C occurred, while the pyrolysis temperature gradually increased. With the loss of volatilization, H, O, and other elements, carbon elements were transformed into coke (the main component is fixed carbon) and accumulated, increasing the fixed carbon content [35]. The fixed carbon content reached steady state when the temperature exceeded 550°C, which was confirmed by the observation of Cheng et al. [36] The possible reason was that the alkali metal in the biomass melted and produced ash at high temperature, thus slowing down the formation rate of fixed carbon [5].

Based on the analysis of environmental benefits, biochar with more fixed carbon plays an important role in
The yield dropped sharply after 3 h of pyrolysis reaction, and there was no significant difference between 2 and 3 h of yield. Fixed carbon content increased slightly with the increase in the residence time from 78.3% to 80.0%, when the holding time exceeded 2 h. In addition, the longer the holding time, the more energy is expended. Therefore, 2 h is the best retention time for pyrolysis reaction to produce biochar given the yield, carbon content, and energy consumption of biochar.

### 3.2 Multi-factor experiment

Yield and fixed carbon content are often the primary indexes considered in the preparation process of biochar. The suitable conditions for biochar preparation were determined through the single-factor experiment, and on this basis, the effect of the interaction of temperature and holding time on the quality of biochar was analyzed.

The central composite design (CCD) of response surface method (RSM) was used to adapt the experimental data to polynomial regression analysis. Temperature (A) and holding time (B) were taken as experimental factors, yield (R1) and fixed carbon content (R2) were taken as responses. The temperature range was 500–600°C and holding time was 1–3 h. The experimental factors and codes are given in Table 2; the test scheme and the results of the CCD are given in Table 3.

#### 3.2.1 Regression model analysis

The experimental results indicated that the yield range was 26.3–30.0%. The equation of the quadratic regression model for biochar yield is given in the following equation:

\[
\text{Yield} \% = 27.33 - 1.80A - 0.5916B + 0.5419AB + 0.5828A^2 + 1.13B^2
\]  

\[ (6) \]

#### Table 2: Experimental factors and codes used in CCD

| Codes | Factors | | |
|-------|---------|---|---|
|       | A (°C)  | B (h) | |
| 1.414 | 600.00  | 3.00 | |
| 1     | 585.36  | 2.71 | |
| 0     | 550.00  | 2.00 | |
| -1    | 514.64  | 1.29 | |
| -1.414| 500.00  | 1.00 | |

The regression model was very significant \((P < 0.01)\), \(R^2 = 0.9826\), suggesting that the predicted value was strongly correlated with the measured value. In the equation of quadratic regression model, \(A, B, \) and \(C\) are linear terms, \(AB\) is interactive terms, and \(A^2, B^2\) are quadratic terms. In the expression above, the positive sign before the coefficient indicates the synergistic effect between the factors, while the negative sign indicates the antagonistic effect. It could be seen that the interaction of temperature and holding time had a synergistic effect on yield.

The fixed carbon content ranged from 72.0% to 80.5%. The equation of quadratic regression model for the fixed carbon content of biochar is given as:

\[
\text{Fixed carbon content} (%) = 77.93 + 3.90A + 1.07B - 0.6556AB - 1.68A^2 - 0.7373B^2
\]  

\[ (7) \]

The regression model was significant \((P < 0.05)\), \(R^2 = 0.9102\); it is well described that the secondary regression equation established by the test was good, and this model can be used to effectively predict the fixed carbon content. The interaction of temperature and holding time was observed to have an antagonistic effect on the fixed carbon content.

#### 3.2.2 Variance analysis of yield and fixed carbon content

The results of the variance analysis of yield are presented in Table 4. The effects of temperature \((A)\) and holding time \((B)\) on yield was extremely significant \((P < 0.01)\), while \(AB\) interaction had a significant effect on the yield.
of biochar ($P < 0.05$). The effects of $A^2$ and $B^2$ were very significant ($P < 0.01$). The results showed that both temperature and holding time had a very significant effect on the yield of biochar, and the importance of two factors affecting decreased in the order temperature > holding time. The interaction between temperature and holding time had a significant influence on yield.

The results of the fixed carbon content variance analysis are presented in Table 5. $A$ had an extremely significant effect on the fixed carbon content of biochar ($P < 0.01$), whereas the effect of $B$ and $AB$ interaction was not significant ($P > 0.05$). Temperature was observed to have a great significant effect on fixed carbon content, while the retention time and their interaction had no significant effect.

### 3.2.3 Model data adequacy check

Through the experimental design of CCD, the actual data were obtained through experiments and the predicted response (yield and fixed carbon content of biochar) was provided by the RSM model.

Relevant studies showed that the variable data points on the diagonal between the predicted value and the actual value indicate the adequacy of the model [38]. It could be seen from Figure 3 that all the points fluctuate on the diagonal, indicating that the actual data were in good agreement with the predicted value and the model established has high reliability.

### 3.2.4 Effects of the interaction of pyrolysis temperature and holding time on yield and fixed carbon content

Design-expert software was used to draw a response surface plot and a contour map in order to more intuitively reflect the rule of influence of factors interaction on biochar. The interaction of temperature and holding time on the yield of biochar is shown in Figure 4. The change of contour lines along the temperature axis was relatively dense, indicating that the effect of temperature on

![Table 4: Variance analysis of yield](image1)

| Source | Sum of squares | Degree of freedom | Mean square | $F$ value | $P$ value |
|--------|----------------|------------------|-------------|-----------|-----------|
| $A$    | 12.80          | 1                | 12.80       | 298.14    | <0.0001   |
| $B$    | 1.39           | 1                | 1.39        | 32.28     | 0.0007    |
| $AB$   | 0.28           | 1                | 0.28        | 6.57      | 0.0374    |
| $A^2$  | 0.58           | 1                | 0.58        | 13.61     | 0.0078    |
| $B^2$  | 2.19           | 1                | 2.19        | 50.93     | 0.0002    |

![Table 5: Variance analysis of fixed carbon content](image2)

| Source | Sum of squares | Degree of freedom | Mean square | $F$ value | $P$ value |
|--------|----------------|------------------|-------------|-----------|-----------|
| $A$    | 60.30          | 1                | 60.30       | 60.67     | 0.0001    |
| $B$    | 4.50           | 1                | 4.50        | 4.53      | 0.0708    |
| $AB$   | 0.41           | 1                | 0.41        | 0.42      | 0.5398    |
| $A^2$  | 4.85           | 1                | 4.85        | 4.88      | 0.0628    |
| $B^2$  | 0.93           | 1                | 0.93        | 0.94      | 0.3644    |

![Figure 3: The relationship between the actual data of the model and the predicted data: (a) yield, (b) fixed carbon content.](image3)
biochar yield was greater than that of holding time. In the ranges of factor levels used in this experiment, the yield of biochar tended to be maximum when the pyrolysis temperature was 508°C, and the holding time was 1.1 h, which was 32.0%. The yield was minimized (reaching 26.2%) in biochar prepared at 597°C and retained for 2.1 h. When the holding time rose from 1 to 3 h, the yield to 500°C, 550°C, and 600°C decreased by 1.6%, 1.8%, and 1.1%, respectively. As the temperature increased, the role of holding time presented a tendency to increase and then decrease, which indicated that the holding time has a greater effect on the yield at around 550°C. When the temperature rose from 500°C to 600°C, the yield at 1, 2, and 3 h declined by 4.0%, 3.5%, and 2.5%, respectively. It demonstrated that temperature had a greater impact on yield in less holding time.

A response surface plot and a contour map of the interaction between temperature and holding time on fixed carbon content are shown in Figure 5. In the factor level range of this experiment, the fixed carbon content tended to reach its maximum value (80.2%) when the temperature was 600°C and the holding time was 2.3 h. The fixed carbon content was found to minimize (71.6%) in the biochar prepared at 503°C and retained for 1.5 h. When the holding time rose from 1 to 3 h, the fixed carbon content at 500°C, 550°C, and 600°C increased by 2.6%, 2.2%, and 1.2%, respectively. It could be observed that the effect of holding time on fixed carbon content was more obvious at a lower temperature. When the temperature rose from 500°C to 600°C, the yield at 1, 2, and 3 h increased by 7.3%, 7.8%, and 6.5%, respectively. It indicated that the temperature had a greater effect on the
fixed carbon content while the holding time was 2 h, and the influence of temperature on fixed carbon content of biochar both decreased when the retention time was lower or higher.

The effect of holding time on yield and fixed carbon content was more obvious in low-temperature region, and that of temperature was more significant in relatively lower holding time region. These findings indicated that the effect of holding time on the pyrolysis process was associated with temperature. As described by Williams and Besler [39], at pyrolysis temperature greater than 500°C, the biochar formation process had progressed to the maximum extent in a short time, with the increase of holding time, the properties of biochar changed little. This observation was consistent with the results of Braadbaart and Poole [40] and Chen et al. [41].

Judging from the steepness of the response surface graph and the ellipticity of the contour line, the effect of temperature on yield and fixed carbon content was greater than that of holding time, indicating that temperature plays a more important role in biomass pyrolysis and carbonization, which was consistent with variance analysis. While at a certain temperature, the increase in holding time mainly changed the surface and internal structure of the biochar but had little effect on the extent of pyrolysis of biomass components. Only by increasing the temperature can the pyrolysis reaction continue to progress, further affecting the yield and fixed carbon content of biochar.

3.2.5 Optimal process condition prediction and validation

According to the abovementioned equation and response surface graph, two inspection indicators (yield and fixed carbon content) were computed, and the optimal process conditions were: \( A = 529.75, B = 2 \), which indicated the theoretical value of the yield and fixed carbon content was 28.2% and 76.1% under the conditions of 529.75°C and holding time was 2 h. Under these preparation conditions, it is possible to maintain a relatively high yield and fixed carbon content and can prevent the damage of structure and the energy waste caused by high temperature and too long holding time.

The optimized process conditions were used to verify the experiment. In actual operation, the conditions were adjusted to a pyrolysis temperature of 530°C, with a holding time of 2 h. Under these conditions, the yield of biochar was 28.1%, and the fixed carbon content was 77.8%, which is very close to the predicted value, indicating that the model was reliable and reasonable, and has certain guiding significance.

3.3 Estimation of carbon sequestration potential

China is blessed with biomass resources. In 2017, China’s crop straw collection was 827 million tons [42], and most of the methods of use are mainly for primitive rural cooking, heating, and ranching. With the severity of the global environment and enhanced awareness of protection, the use of straw resource has become a hot topic of research. At present, straw energy utilization in China is primarily in the form of gasification by pyrolysis, biogas formed by fermentation, solidified forming, and carbonization. The specific situation is presented in Table 6. It should be noted that the amount of carbonization has increased year by year while the amount of gasification of pyrolysis and fermentation in biogas has decreased. It could be obtained that the formation of biochar from biomass carbonization has become the main trend of straw utilization.

Qinghai has a huge potential for carbon sequestration, with CO₂ emission of 5,490.62 million tons in 2019 [27]. The agricultural production mode of high input and high output has caused a significant decrease in soil carbon storage capacity and an increase in environmental carbon load, producing a large number of straw residues that have not been effectively treated. It is of great significance to establish a long-term mechanism of sustainable straw comprehensive utilization for carbon sequestration and emission reduction.

Table 6: Utilization of straw resources in China

| Year | Pyrolytic gasification for gas supply \((10^3 \text{ households})\) | Methane for gas supply \((10^3 \text{ households})\) | Straw curing yield \((\text{t})\) | Straw carbonization yield \((\text{t})\) |
|------|--------------------------------------------------|-------------------------------------------------|-------------------------------|-----------------------------------|
| 2015 | 12.34                                            | 8.14                                            | 4,934,886                     | 162,810                           |
| 2016 | 9.80                                             | 7.49                                            | 4,902,847                     | 287,647                           |
| 2017 | 7.68                                             | 6.64                                            | 5,738,891                     | 300,070                           |
### Table 7: Carbon emission from combustion and carbon sequestration potential of pruned wolfberry branches

| Year | Branches yield (kt) | CO emissions (kt) | CO₂ emissions (kt) | Carbon emissions (kt) | CF applied by biochar to soil (kt) |
|------|---------------------|-------------------|--------------------|-----------------------|-----------------------------------|
| 2015 | 133.16              | 12.25             | 201.73             | 59.73                 | 30.00                             |
| 2016 | 143.55              | 13.21             | 217.48             | 64.40                 | 32.34                             |
| 2017 | 150.98              | 13.89             | 228.73             | 67.73                 | 34.01                             |
| 2018 | 159.89              | 14.71             | 242.23             | 71.73                 | 36.02                             |
| 2019 | 152.82              | 14.06             | 231.52             | 68.56                 | 34.42                             |

#### 3.3.1 Estimation of the number of burning branches

Data on the planting area of wolfberry in Qinghai province were derived from the Qinghai Statistical Yearbook. According to the pruned branches amount of 4500 kg·hm⁻² [43], calculated the yield of discarded wolfberry branches. As can be seen from Table 7, the annual pruned waste wolfberry branches in Qinghai province were as high as 159.89×10³ t, which has a good prospect of biomass resource reusing.

#### 3.3.2 Estimation of carbon emissions from branch combustion

Assuming that all branches were burned, parameters related to branch combustion are shown in Table 7. At present, there are few studies on carbon emissions from abandoned fruit tree branches. In this study, measured data on the combustion of crop straw at home and abroad were used as carbon emission factors for branch combustion. CO and CO₂ emission factors were calculated as 92 and 1,515 g·kg⁻¹, respectively [44]; the total amount of CO and CO₂ emission from burning of wolfberry branches in Qinghai province in recent 5 years was estimated. Similar to the changing trend of discard branches, CO and CO₂ emission increased significantly and declined in 2019. If all the discarded wolfberry branches in Qinghai province were used for biochar preparation, carbon emissions to the atmosphere could be reduced annually from 59.73×10³ to 71.73×10³ t.

#### 3.3.3 Effects of biochar on soil carbon cycling and soil sequestration

The extensive incorporation of biochar into soils would inevitably affect the amount and composition of SOC [45]. Following the addition of biochar, the stable organic carbon fraction of biochar would directly increase the amount of organic carbon through physical mixing [46]. The additions to soil indicated that biochar has the potential to improve crop growth and yield [47], which would affect the biological fixation of biochar in soil. In addition, biochar has been found in the Amazon Canal Basin and could be stored for thousands of years in the soil [48]. However, there are also studies showing that biochar has stimulated soil body organic carbon mineralization after entering the soil and it will also decompose mineralization and increase greenhouse gas emissions [26]. It can be seen that the carbon sequestration capacity of biochar is closely related to the properties of biochar (e.g., pH and CEC) and soil (e.g., soil porosity and soil aggregation), and when different biochar are added to different soils, the result is huge.

Some instability carbon in biochar will be decomposed by biology and the section of stable carbon will be stored in soil [49]. Therefore, the carbon sequestration capacity of biochar is only considered to be the stable part of biochar in soil. One study showed that about 20% of the unstable part of biochar was easy to decompose [50] and the result was used as computational data in this study. The potential for carbon sequestration and emission reduction from the wolfberry branch pyrolysis system in Qinghai province is shown in Table 7. The results showed that the effect of carbon sinks could be generated after biomass carbonization, and the carbon sequestration potential of biochar was from 30.00×10³ to 36.02×10³ t. If all wolfberry branches were used for biochar preparation, 34.42×10³ t of carbon could be fixed in 2019. It can be seen that the development of biochar technology using crop straw has an obvious effect on reducing carbon emissions in Qinghai province while improving the energy structure.

Ibarrola et al. [51] explored the carbon sink of ten different biomass materials under slow pyrolysis conditions, and the results showed that the CF potential varied from 0.07 to 1.25 t of CO₂ per ton of raw materials. Roberts et al. [50] calculated the carbon sequestration capacity of corn stalk as 0.86 t of CO₂ per ton. The amount of carbon sequestration in the above research is slightly different...
from that in this study (each ton of biochar can fix 0.23 t of CO$_2$ on average), the possible reason is that the properties of derived biochar are different due to the different contents of various components of biomass, and different pyrolysis conditions make the yield of biochar in this study relatively lower.

4 Conclusion

The appropriate carbonization condition of pruned wolfberry branches was obtained. As the temperature and holding time increased, the yield of biochar gradually decreased, while the fixed carbon content increased progressively. Both temperature and holding time had extremely significant effects on yield, and the interaction had significant effects. Temperature had an extremely significant effect on fixed carbon content, while holding time and the interaction had no significant effect. Furthermore, the effects of temperature on yield and fixed carbon content were greater than those of holding time. The preparation conditions optimized by RSM were that the temperature was 529.75°C and the holding time was 2 h. The predicted values of yield and fixed carbon content were 28.2% and 76.1%, respectively. The above conditions were modified according to the actual situation, and the final conditions of optimization were the temperature of 530°C and holding time of 2 h. The yield and fixed carbon content obtained were 28.1% and 77.8%, respectively, close to the theoretical predicted value, indicating the model was accurate and reliable for optimizing the preparation conditions of biochar, and could better predict the actual yield and fixed carbon content of biochar.

The potential for carbon sequestration of biochar generated by wolfberry branches was evaluated. If all pruned wolfberry branches in Qinghai province were used for biochar preparation, $6.85 \times 10^5$ t of carbon emission from combustion in the atmosphere could be reduced annually. If the biochar were applied to soil, about $34.42 \times 10^5$ t of carbon could be fixed.

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