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Effects of biochar from *populus alba × populus berolinensis* and *pinus sylvestris var. mongolica* application on soil physicochemical properties

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This study examined the effects of biochar produced from forestry waste (*Populus alba×P. berolinensis* and *Pinus sylvestris var. mongolica* branches and leaves) on soil physicochemical properties through a 60-day static incubation experiment under varying pyrolysis temperatures (300, 500, and 700 °C) and application rates (1%, 3%, and 5% (w/w)). Results indicated that biochar application enhanced soil available potassium content and pH to different extents. Notably, the most pronounced effect was observed with a 5% application rate of *Populus alba×P. berolinensis* leaves biochar pyrolyzed at 700 °C, which increased available potassium by 266.39% and pH by 9.82% compared to the control. At a 5% application rate, biochar produced from *Populus alba×P. berolinensis* leaves pyrolyzed at 300 °C increased soil ammonium nitrogen content by 49.27% and available phosphorus content by 141.68% compared to the control. Furthermore, biochar improved soil organic Matter content, water content, and aggregation. Specifically, the most significant increases were seen with a 5% application rate of *Populus alba×P. berolinensis* branch biochar pyrolyzed at 300 °C, raising organic Matter by 320.03% and water content by 30.61% compared to the control. Regarding soil aggregate distribution, a 5% application rate of *Pinus sylvestris var. mongolica* branch biochar pyrolyzed at 300 °C significantly increased the macroaggregate fraction while reducing microaggregates and silt-clay fractions. In conclusion, the application of forestry waste-derived biochar demonstrates potential for improving soil physicochemical properties, with pyrolysis temperature, feedstock source, and application rate all significantly influencing these improvement effects.

Keywords Biochar, Forestry waste, Soil physicochemical properties, Feedstock sources, Pyrolysis temperature

The biochar is a type of solid substance with high aromaticity, produced from organic waste through high-temperature pyrolysis under oxygen-limited conditions[1]. It contains elements such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and phosphorus (P), and is characterized by a large specific surface area and strong adsorptive properties[2]. The application of biochar can enhance soil fertility. For instance, incorporating straw biochar into winter wheat soil can effectively increase the levels of soil-available phosphorus, ammonium nitrogen, and nitrate nitrogen, while also notably boosting crop yield[3]. For sandy soil, the addition of citric acid-aged cotton stalk biochar aids in nitrogen retention, effectively elevating soil nitrogen and organic matter content[4]. Furthermore, biochar contributes to improving soil structural stability. For example, adding biochar to clay loam soil in Heihe, Heilongjiang Province, significantly increases the proportion of macro-aggregates, thereby enhancing soil structure[5]. Simultaneously, it enhances soil water retention capacity[6]which positively impacts soil structure. Different preparation conditions and application rates of biochar exhibit varying effects on soil physicochemical properties. For instance, high-temperature biochar is more effective in improving soil pH than low-temperature biochar[7]and the comprehensive improvement effect of 5% biochar is superior to

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that of 10%[8]. Additionally, wheat straw biochar demonstrates better adsorption capacity for phosphorus in soil compared to corn straw and rice straw biochars[9]indicating that different types of biochar have distinct effects on soil nutrient absorption and utilization. Therefore, by adjusting the feedstock sources and amount of biochar applied, soil physicochemical properties can be targetedly improved.

Currently, the raw materials primarily used for producing biochar are agricultural waste and sludge. However, there is relatively little research on biochar produced from forestry waste, both domestically and internationally. In China, a significant amount of forestry waste is generated annually during forestry production and processing[10]. In 2020, the total resource volume of forestry waste in China amounted to approximately 350 million tons, with an annual output of roughly 195 million tons of utilizable waste resources stemming from natural tree growth and artificial harvesting[11]. Despite some of these biomass resources naturally withering and decomposing, entering the soil cycle, the degree of their development and utilization remains low. The utilization rate of forestry waste resources in China is less than 10%[12]. Converting forestry waste into biochar and applying it to the soil offers a dual benefit, it effectively utilizes forestry waste and enhances soil quality[10]. For instance, Eucalyptus biochar prepared at high temperatures boasts a large specific surface area, which increases the soil's adsorption of nitrogen[13]. On the other hand, *Hevea brasiliensis* biochar naturally contains a substantial amount of available phosphorus, significantly increasing the soil's phosphorus content[14]. Furthermore, during the production of *Populus* L. biochar, a significant quantity of inorganic minerals and ashes, such as carbonates and phosphates, are formed. The presence of these substances renders the biochar alkaline, thereby elevating the soil's pH value[15]. Therefore, converting forestry waste into biochar not only addresses the inadequate utilization of forestry biomass resources in China but also provides an effective means for soil improvement.

Populus alba × *P. berolinensis* and *Pinus sylvestris var. mongolica* are tree species that are widely distributed across Northeast China. Among them, *Populus alba* × *P. berolinensis* serves as a primary tree species for constructing water conservation forests, slope erosion control forests, and gully bank protection forests[16]. Meanwhile, *Pinus sylvestris var. mongolica*, with its deep roots, has the ability to absorb and utilize deep soil water, thereby reducing the amount of deep infiltration replenished by rainfall[17]. Both species exhibit rapid growth and offer good economic benefits[18]. Furthermore, the waste biomass of these two species represents a rich resource, primarily comprising components such as hemicellulose, lignin, and pectin, which holds great potential for comprehensive resource utilization[19]. For instance, the sawdust of Pinus sylvestris var. mongolica and its biochar possess excellent adsorption capacity, effectively removing Cd^{2+} from wastewater[20]. Additionally, biochar produced from the fallen leaves of Populus alba × P. berolinensis not only adsorbs heavy metal ions such as Pb^{2+} in wastewater but also has leaf extracts that can inhibit bacteria like *Pseudomonas aeruginosa* and even eliminate *Aspergillus niger*[21]. However, there are still limited reports on the impact of biochar derived from these two types of waste on soil physicochemical properties. Based on previous research, we hypothesize that forestry waste biochar improves soil physicochemical properties. Furthermore, we postulate that feedstock types and pyrolysis temperatures significantly influence these beneficial effects. Therefore, to test this hypothesis, we conducted an investigation into how biochar derived from the branches and leaves of *Populus alba* × *P. berolinensis* and *Pinus sylvestris var. mongolica*, produced at different pyrolysis temperatures, affects soil physicochemical properties when applied at varying rates.

Materials and methods

Experimental materials

The leaves and branches of *Populus alba* × *P. berolinensis* and *Pinus sylvestris var. mongolica* were collected from Zhanggutai Forest Farm, located in Zhangwu County, Fuxin City, Liaoning Province, China. The tree species were identified by the staff of Zhanggutai Forest Farm, and the samples were directly obtained from the respective trees. Since the leaves and branches we collected are not botanical specimens, they were not deposited in a public specimen repository. Zhanggutai Forest Farm serves as an experimental base for the Liaoning Academy of Agricultural Sciences, and we were granted permission to collect these leaves and branches for Further experimental purposes. The collected leaves and branches were thoroughly washed with deionized water and then prepared as biochar through anaerobic pyrolysis at 300, 500, and 700 °C for 6 h, respectively. The prepared biochars were labeled as follows: *Populus alba* × *P. berolinensis* leaves (YY300, YY500, YY700), *Populus alba* × *P. berolinensis* branches (YZ300, YZ500, YZ700), *Pinus sylvestris var. mongolica* leaves (ZY300, ZY500, ZY700), and *Pinus sylvestris var. mongolica* branches (ZZ300, ZZ500, ZZ700). The properties of different biochars vary significantly, particularly for those derived from *Populus alba* × *P. berolinensis*, with specific physicochemical properties detailed in our previously published articles[22]. The soil used in the experiment was collected from farmland in Shenbei New Area, Shenyang City, Liaoning Province, China, and its basic chemical properties are outlined in Table 1.

Soil incubation experiments design

Weigh 35 g of air-dried soil samples that have passed through a 2-mm sieve and place them in 250 mL culture bottles. The biochar derived from forestry waste, which was pyrolyzed at temperatures of 300, 500, and 700 °C, was thoroughly mixed with soil at addition levels of 0% (CK), 1%, 3% and 5% (w/w), respectively. Add 7 mL distilled water, seal the mouths of the bottles with plastic wrap while ensuring air permeability. Place the samples

	Organic matter (g/kg)	NH_4^+-*N* (mg/kg)	Available potassium (mg/kg)	Available phosphorus (mg/kg)	pH
Soil	28.99	14.42	117.20	38.80	6.95

Table 1. Chemical properties of the soil.

in a well-ventilated laboratory with natural Light at 25 °C for culturing. To Maintain soil moisture and microbial activity, distilled water was added to each culture bottle every 7 days. Equal volumes were replenished per bottle during each watering event. All treatments were replicated three times. On the 60th day, take samples to measure soil physicochemical properties, including available phosphorus (AP), available potassium (AK), ammonium nitrogen (AN), and organic matter (SOM).

Determination of physical and chemical properties

A pH meter (Sartorius PB-10) was used to measure the pH values of soils. The soil aggregate was determined using a 2000 Laser Particle Size Analyzer. The moisture content was determined by the oven-drying method. The potassium dichromate oxidation with external heating method was used to measure SOM[11]. AN was determined by alkaline diffusion method. The determining method of AK was atomic absorption flame spectrophotometry. AP was determined by $NaHCO_3$ extraction followed by molybdenum vanadate colorimetry[12].

Statistical analyses

Statistical analysis and processing of the data were conducted using Excel 2019, whereas one-way ANOVA was performed using SPSS 19.0. Graphical illustrations were created using Origin 2021.

Results and discussion

Effects of Biochar application on soil pH

As can be observed in Fig. 1, the soil pH increased significantly with the addition of biochar. Notably, biochar derived from the leaves of Populus alba×P. berolinensis exhibited the largest increase in soil pH, ranging from 2.05 to 4.99%, 4.69–7.92%, and 5.87–9.82% higher than the CK, respectively. This could be attributed to the abundance of various oxygen-containing functional groups (C = O, C-O-C, etc.) on the surface of biochar, which can react with protons in the soil in the form of anions[23]thereby elevating the soil pH. Regarding the biochar content, YY700, ZY700, ZZ700, and YZ700 had significant effects on soil pH at a 5% application rate, with increases of 9.82%, 7.12%, 7.04%, and 5.84% compared to the CK, respectively, in the order of YY700 > ZY700 > YZ700 > ZZ700. This suggests that biochar from the leaves of *Populus alba×P. berolinensis* has the most pronounced effect on increasing soil pH, potentially due to its higher ash content[22]. For biochars produced at different pyrolysis temperatures, the application of biochar at 700 °C had a significantly greater impact on soil pH compared to other temperatures. This may be because as the pyrolysis temperature increases, the number of alkaline functional groups in biochar rises[22]enabling a more effective improvement in soil pH.

Effects of Biochar application on soil NH_4^+-N content

NH_4^+-N is a vital source of nitrogen in soil[24]. As depicted in Fig. 2, the soil NH_4^+-N content steadily rises with an increase in biochar application. Notably, biochar derived from the leaves of *Populus alba×P. berolinensis* demonstrates the most significant effect on this increase, exceeding the CK by 15.65–19.35%, 27.16–32.69%, and

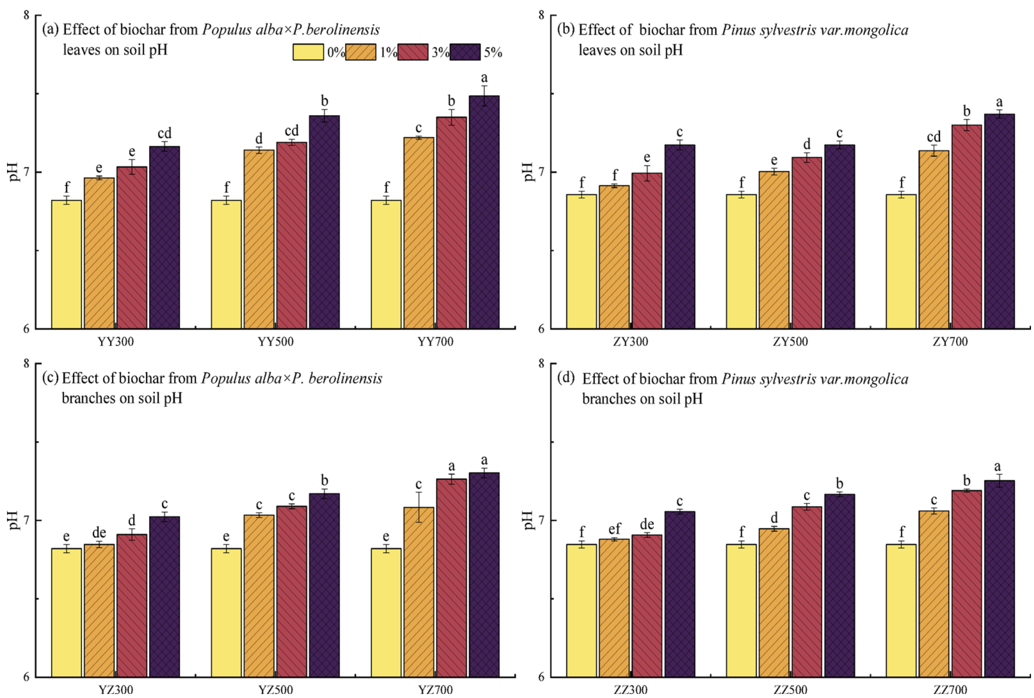

Fig. 1. Effects of biochar from *Populus alba×P. berolinensis* leaves (a), *Pinus sylvestris var. mongolica* leaves (b), Biochar from *Populus alba×P. berolinensis* branches (c) and *Pinus sylvestris var. mongolica* branches (d) on soil pH.

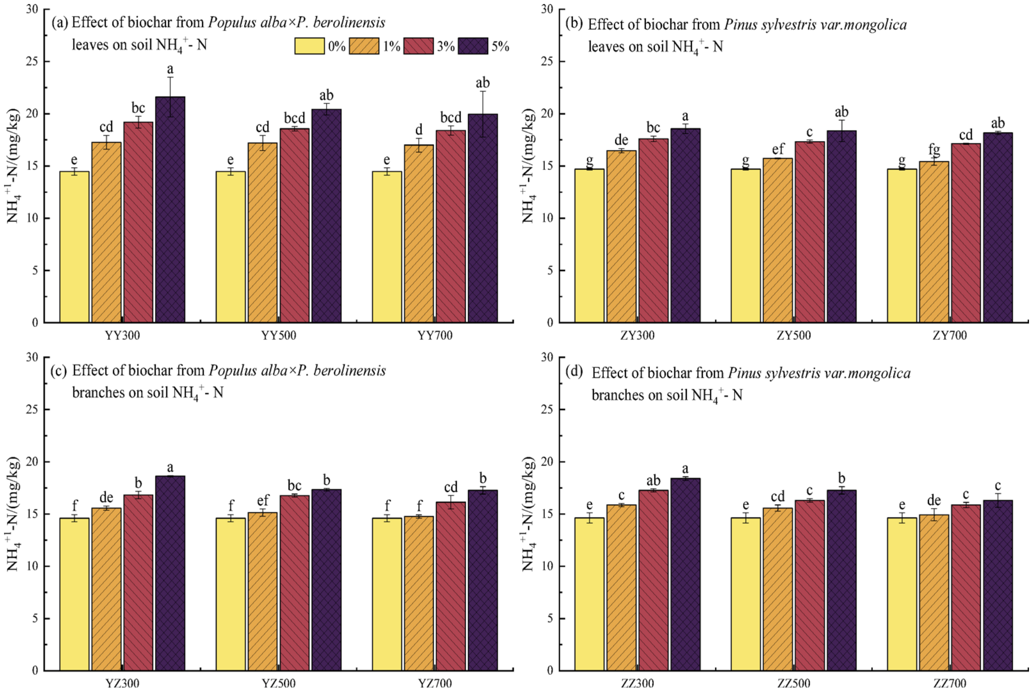

Fig. 2. Effects of biochar from *Populus alba×P. berolinensis* leaves (**a**), *Pinus sylvestris var. mongolica* leaves (**b**), *Populus alba×P. berolinensis* branches (**c**) and *Pinus sylvestris var. mongolica* branches (**d**) on soil NH_4^+- N.

38.01–49.27%, respectively. This may be attributed to biochar's ability to adsorb NH^{4+}-N in the soil and reduce nitrogen leaching losses, thereby enhancing the soil's NH^{4+}-N content[25]. In terms of biochar content, the most notable effects on soil NH4+-N content were observed with YY300, YZ300, ZY300, and ZZ300 at a 5% addition rate, with increases of 49.27%, 24.86%, 26.33%, and 26.03% compared to the CK, respectively, in the order of YY300 > ZY300 > YZ300 > ZZ300. This suggests that leaf-based biochars have a more pronounced impact on soil ammonium nitrogen content than branch-based biochars. Furthermore, studies by Luo et al. have indicated that leaf-based biochars exhibit superior ammonium nitrogen adsorption capabilities compared to branch-based biochars, aiding in reducing ammonium nitrogen losses[26]. Among leaf-based biochars, biochar from *Populus alba×P. berolinensis* leaves had the most significant effect on NH^{4+}-N content. This could be due to broad-leaved trees generally having higher NH^{4+}-N content than coniferous trees, contributing to elevated soil NH^{4+}-N levels[27]. For biochars produced at varying pyrolysis temperatures, the 300 °C biochar had the most notable impact, potentially because low-temperature pyrolysis biochars achieve suitable cation exchange capacity (CEC) and C/N ratios, which facilitate nutrient mineralization[28]. Additionally, studies have demonstrated that low-temperature pyrolysis biochars possess strong ammonium nitrogen adsorption capabilities[29]. Therefore, the 300 °C biochar can significantly increase soil NH_4^+-N content.

Effects of Biochar application on soil available potassium content

Available potassium in the soil can be effectively absorbed and utilized by plants[30]. As illustrated in Fig. 3, the soil's available potassium content rises with an increase in biochar addition. Notably, biochar derived from *Populus alba×P. berolinensis* leaves has the most pronounced effect on soil available potassium content, showing increases ranging from 102.22 to 179.28%, 107.01–224.25%, and 154.25–266.39% compared to the CK, respectively. This is attributed to the enhancement of soil cation exchange capacity with biochar application, coupled with a reduction in potassium leaching loss from the soil[31]. Regarding the amount of biochar applied, a 5% addition results in a significant increase in soil available potassium content. Specifically, the soil available potassium content for YY700, ZY700, YZ700, and ZZ700 increases by 266.39%, 255.27%, 238.23%, and 221.29%, respectively, compared to the CK, following the trend of YY700 > ZY700 > YZ700 > ZZ700. This further confirms that biochar from *Populus alba×P. berolinensis* leaves has the most significant impact on soil available potassium content. For biochars produced at different pyrolysis temperatures, the 700 °C biochar notably elevates soil available potassium content. This may be due to the high potassium content in the ash of biochar, which increases as the pyrolysis temperature rises[22,32]. Consequently, biochar produced at a pyrolysis temperature of 700 °C significantly enhances soil available potassium content.

Effects of Biochar application on soil available phosphorus content

Available phosphorus is the most effective nutrient for crops in soil[33]. As shown in Fig. 4, the content of available phosphorus in soil increases with the addition of biochar. Among them, biochar derived from the leaves of Populus alba×P. berolinensis has a significant impact on soil available phosphorus content, with increases ranging from 44.74 to 93.61%, 65.53–101.84%, and 73.68–141.68% compared to the CK, respectively. This

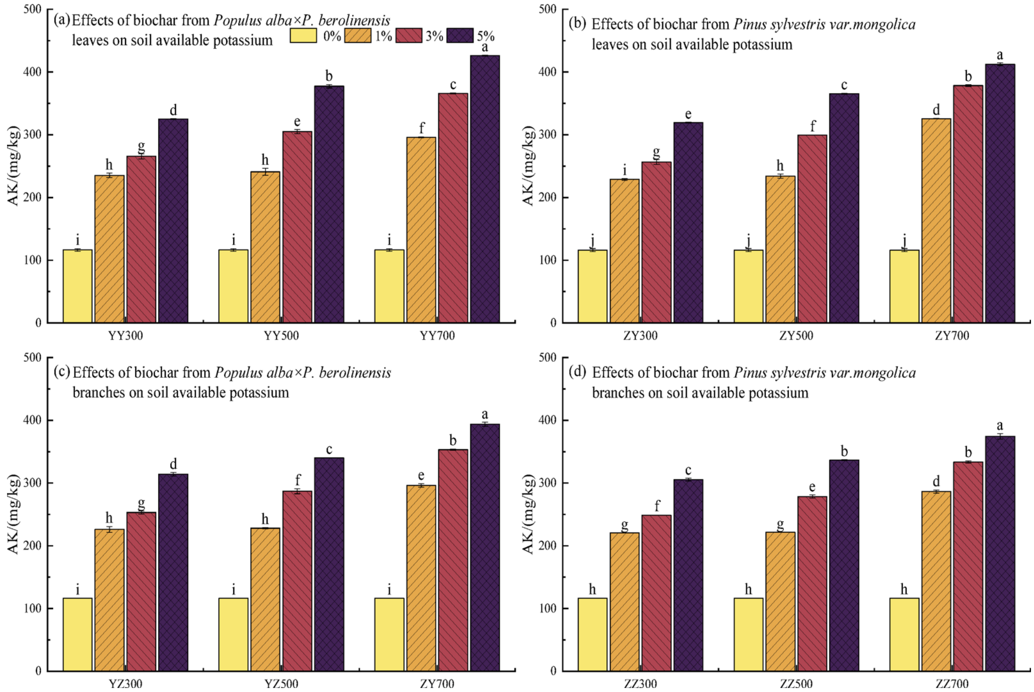

Fig. 3. Effects of biochar from *Populus alba×P. berolinensis* leaves (**a**), *Pinus sylvestris var. mongolica* leaves (**b**), *Populus alba×P. berolinensis* branches (**c**) and *Pinus sylvestris var. mongolica* branches (**d**) on soil available potassium.

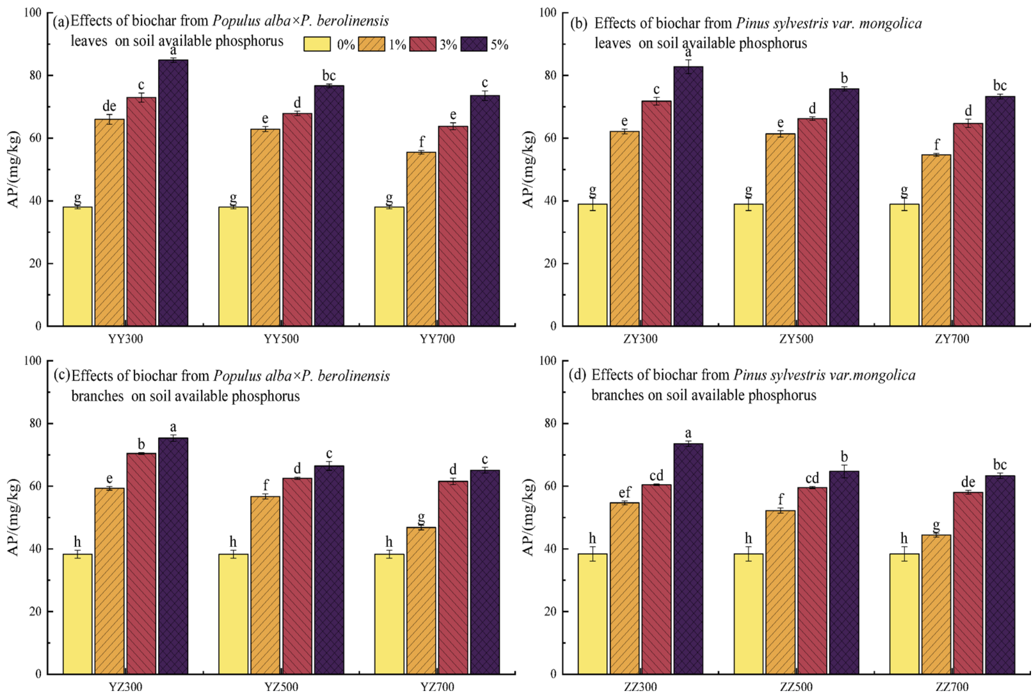

Fig. 4. Effects of biochar from *Populus alba×P. berolinensis* leaves (**a**), *Pinus sylvestris var. mongolica* leaves (**b**), *Populus alba×P. berolinensis* branches (**c**) and *Pinus sylvestris var. mongolica* branches (**d**) on soil available phosphorus.

is because the ash content of biochar contributes to the increase in soil available phosphorus content[34]and biochar from *Populus alba×P. berolinensis* leaves has a higher ash content than other biochars[22]. Regarding the biochar content, YY300, ZY300, YZ300, and ZZ300 showed significant improvement effects at a 5% addition level, with increases of 141.68%, 112.78%, 96.68%, and 91.59% compared to the CK, respectively. The order of effectiveness is YY300 > ZY300 > YZ300 > ZZ300. Therefore, leaf-based biochar has a more significant impact on soil available phosphorus content than branch-based biochar. This may be due to the relationship between available phosphorus and plant growth and metabolism, with leaves being the primary site for photosynthesis[35]. Consequently, leaf-based biochar contains more available phosphorus. Additionally, the content of soil available phosphorus treated with biochar decreases as the biochar pyrolysis temperature increases. This may be because higher pyrolysis temperatures reduce the residual soluble phosphate content and affect the biochar's adsorption capacity for phosphate roots, thereby limiting the increase in available phosphorus[36]. Therefore, the increase in soil available phosphorus content gradually diminishes with rising biochar pyrolysis temperatures.

Effects of Biochar application on soil organic matter

The results of the determination of soil organic matter content are presented in Fig. 5. As the amount of biochar added increased, the soil organic matter content rose gradually. Notably, the biochar derived from the branches of Populus alba×P. berolinensis exhibited the greatest increase in soil organic Matter. Specifically, it was 173.34–320.03%, 162.88–253.35%, and 146.69–240.02% higher than that of the CK, respectively. This may be attributed to the fact that biochar itself contains organic carbon, thereby augmenting the exogenous organic carbon content in the soil[37]. Furthermore, the incorporation of biochar into the soil may alter the availability of organic carbon, enhancing the soil's capacity to retain organic carbon and indirectly boosting its organic matter content[38]. Regarding the biochar content, YY300, ZY300, YZ300, and ZZ300 demonstrated the most pronounced improvement in soil organic Matter content at a 5% addition level. Compared to CK, the increases were 320.03%, 274.6%, 299.03%, and 244.28%, respectively, in the order of YZ300 > ZZ300 > YY300 > ZY300. This suggests that branch-based biochar has the most significant promotional effect on soil organic matter content, potentially due to its higher content of undecomposed lignin, which contributes to the formation of more organic carbon[39]. Moreover, studies indicate that broad-leaved tree species are more inclined to form stable organic matter than coniferous tree species[40]. Therefore, the impact of biochar from *Populus alba×P. berolinensis* on soil organic matter content is more pronounced than that of biochar from *Pinus sylvestris var. mongolica*. For biochars pyrolyzed at varying temperatures, those pyrolyzed at 300 °C significantly elevated soil organic matter content. This could be due to the higher aromaticity and enhanced self-stability of biochars pyrolyzed at higher temperatures, which contain fewer easily degradable components[22]. Additionally, biochars pyrolyzed at 300 °C possess more easily oxidized carbon (EOC)[41]further increasing the organic matter content in the soil.

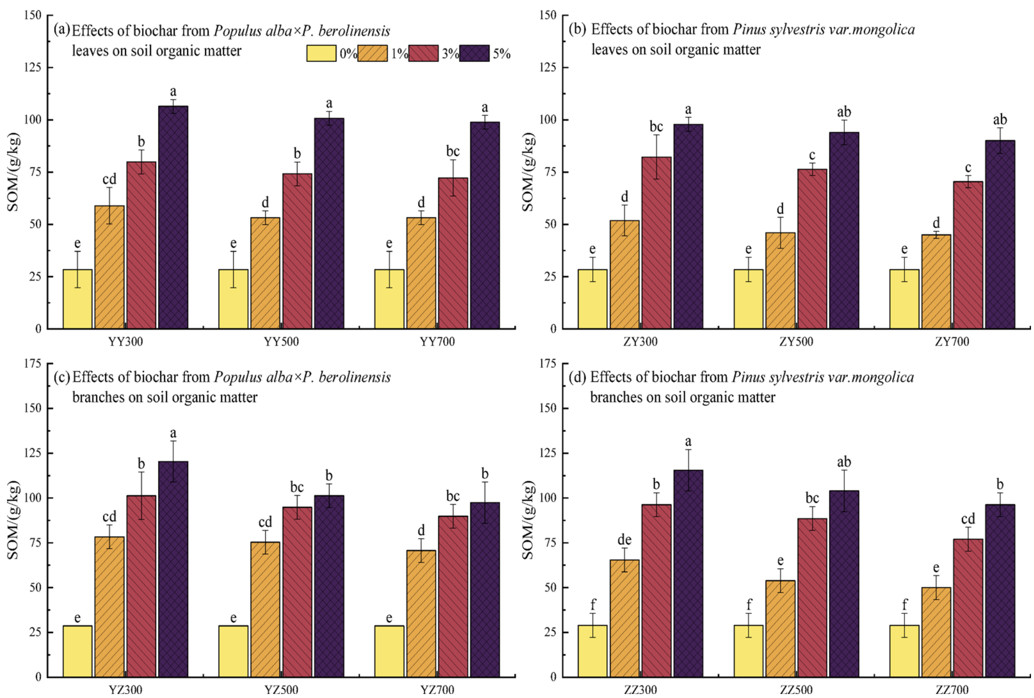

Fig. 5. Effects of biochar from *Populus alba×P. berolinensis* leaves (**a**), *Pinus sylvestris var. mongolica* leaves (**b**), *Populus alba×P. berolinensis* branches (**c**) and *Pinus sylvestris var. mongolica* branches (**d**) on soil organic matter.

Effects of Biochar application on soil moisture content

The results of the determination of soil moisture content are presented in Fig. 6. The soil moisture content increased gradually with the increase in biochar addition. Notably, biochar derived from the branches of Populus alba×P. berolinensis significantly elevated the soil moisture content, with increases ranging from 25.51 to 30.61%, 24.42–29.25%, and 22.04–28.37%, respectively, compared to the CK. This is attributed to biochar's abundant porous structure, which, when applied, promotes the formation of soil aggregates, thus enhancing soil moisture conten[42]. Regarding the biochar content, YY300, ZY300, YZ300, and ZZ300 significantly increased soil moisture content at a 5% addition level, with increases of 11.78%, 10.07%, 30.61%, and 26.22% compared to CK, respectively. The order of effectiveness is YZ300 > ZZ300 > YY300 > ZY300. Therefore, the treatment with branch-based biochar had the most prominent effect on boosting soil moisture content, potentially due to its higher organic matter content[43]. The surface of this organic matter features a large number of micropores, which can enhance the soil's water-holding capacity[44]. Furthermore, a higher application rate increases soil porosity and the formation of soil aggregates, thereby improving soil water-holding capacity[45]. Among biochars pyrolyzed at different temperatures, those pyrolyzed at 300 °C have a more pronounced effect on soil moisture content. Among biochars pyrolyzed at various temperatures, those pyrolyzed at 300 °C had a more pronounced effect on soil moisture content. This May be due to the higher hydrophobicity and increased stability of biochars pyrolyzed at higher temperatures. Additionally, biochars pyrolyzed at 300 °C contain more hydrophilic functional groups[22]allowing them to better enhance soil water content. Studies have also shown that as pyrolysis temperature increases, the water-holding capacity of biochar decreases[46]. Therefore, biochars pyrolyzed at 300 °C can significantly increase soil moisture content.

Effects of Biochar application on soil aggregate composition

As evident from Fig. 7, under varying treatment conditions, the content of soil aggregates ranging from 0.053 to 0.25 mm remains the highest. Specifically, for *Populus alba×P. berolinensis* leaf biochar, the range is 53.38–59.02%; for *Pinus sylvestris var. mongolica* leaf biochar, it is 54.87–61.32%; for *Populus alba×P. berolinensis* branch biochar, it is 57–61.32%; and for *Pinus sylvestris var. mongolica* branch biochar, it is 56.9–61.38%. Furthermore, the content of different soil aggregates, in descending order, is as follows: 0.053 ~ 0.25 mm, < 0.053 mm, and 0.25 ~ 2 mm.

The content of silt-clay aggregates smaller than 0.053 mm decreased with the increasing application rate of biochar. Notably, at a 5% addition rate, ZZ300 significantly reduced the soil silt-clay aggregate content by 24.86% compared to CK ($P < 0.05$). However, the impact of biochar application on the content of aggregates ranging from 0.053 to 0.25 mm was not uniform. Specifically, YZ300 had a more significant effect on the microaggregate content at a 5% addition rate, reducing it by 6.01% compared to CK ($P < 0.05$). Additionally, as the amount of biochar added increased, the content of Macroaggregates ranging from 0.25 to 2 mm also increased. Notably, ZZ300 significantly increased the Macroaggregate content by 188.45% compared to CK at a 5% addition rate ($P < 0.05$). The addition of biochar promotes the increase of soil macro-aggregates primarily because its porous nature

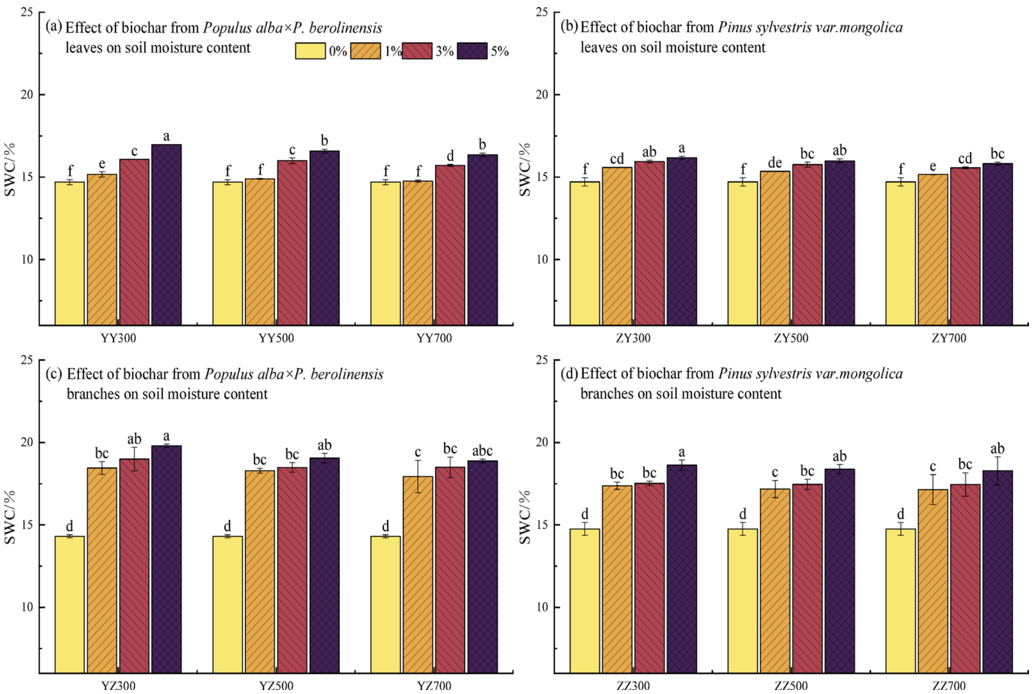

Fig. 6. Effects of biochar from *Populus alba×P. berolinensis* leaves (**a**), *Pinus sylvestris var. mongolica* leaves (**b**), *Populus alba×P. berolinensis* branches (**c**) and *Pinus sylvestris var. mongolica* branches (**d**) on soil moisture content.

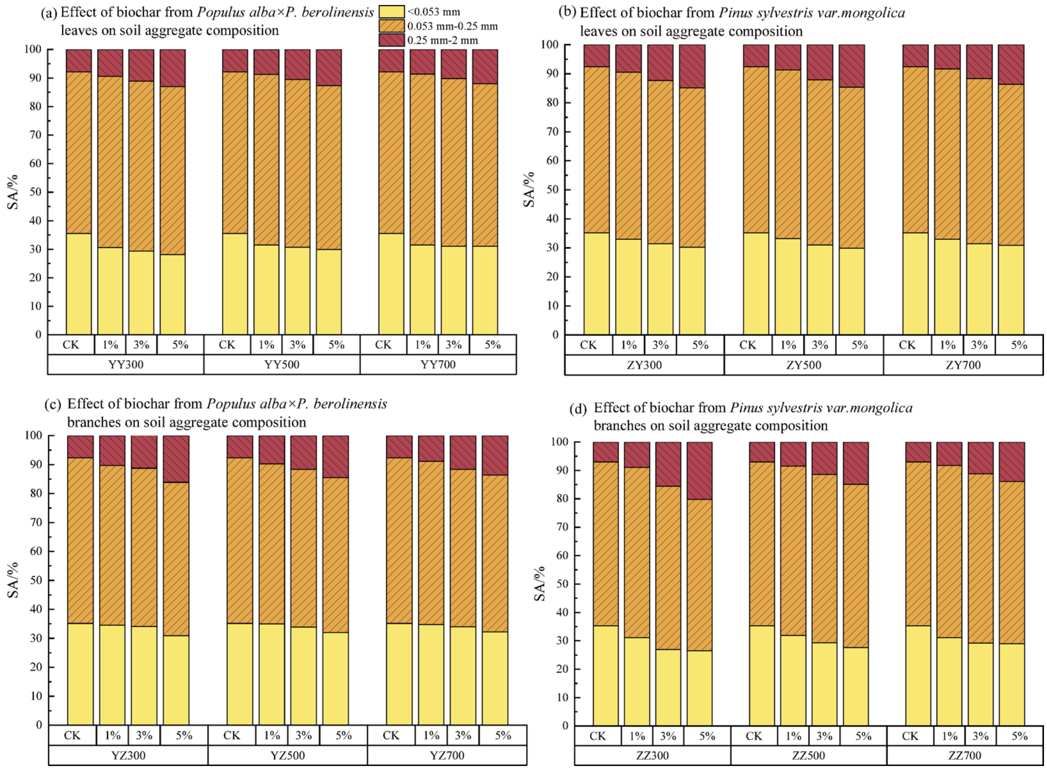

Fig. 7. Effects of biochar from *Populus alba*×*P. berolinensis* leaves (**a**), *Pinus sylvestris var. mongolica* leaves (**b**), *Populus alba*×*P. berolinensis* branches (**c**) and *Pinus sylvestris var. mongolica* branches (**d**) on soil aggregate composition.

provides favorable conditions for the growth and habitat of diverse microorganisms that decompose organic molecules[47]. This enhances the formation of carbon bridges between soil particles, leading to soil aggregation[48]. Biochar derived from branches at lower pyrolysis temperatures demonstrates superior efficacy in promoting soil macro-aggregate formation, primarily attributable to two interconnected mechanisms: (1) The abundant lignin in branch biomass - characterized by high resistance to decomposition - facilitates the development of aromatic carbon skeletons during pyrolysis, which constitute the structural framework of biochar[49]. This configuration significantly enhances the biochar's capacity to adsorb and retain soil organic matter[50]. (2) Lower pyrolysis temperatures preserve higher organic carbon content within the biochar, which elevating soil organic matter levels[51]. These factors synergistically promote soil aggregation through the establishment of organo-mineral associations between soil particles and biochar[52].

Among biochars produced at different pyrolysis temperatures, 300 °C biochar had a more significant impact on macroaggregates. Specifically, compared to CK, YY300, ZY300, YZ300, and ZZ300 increased Macroaggregate content by 19.85% ~ 66.84%, 24.47% ~ 96.69%, 27.96% ~ 109.75%, and 34.33% ~ 188.45%, respectively. This can be represented as: ZZ300 > YZ300 > ZY300 > YY300. This differs from the findings of Ghorbani and Amirahmadi[53]who argued that higher pyrolysis temperatures lead to greater hydrophobicity of biochar, which in turn reduces the dispersion of soil aggregates. This process enhances organo-mineral interactions binding soil particles to the biochar surface, resulting in better improvement effects on soil aggregates. However, biochar produced at lower pyrolysis temperatures contains higher organic matter content, which facilitates the formation of carbon bridges between soil particles and the biochar surface, thereby fostering soil aggregation[54,55]. In this study, the effect of organic matter could have predominated over hydrophobic interactions, resulting in better improvement effects of low-temperature biochar on soil aggregates compared to high-temperature biochar. Additionally, due to the larger specific surface area of *Pinus sylvestris var. mongolica* biochar, while a large specific surface area promotes the formation of carbon bridges between soil particles and the biochar surface[55]resulting in a stronger promoting effect on macroaggregates compared to *Populus alba*×*P. berolinensis* biochar.

Conclusions

The application of biochar derived from forestry waste significantly enhances soil physicochemical properties. Specifically, biochars produced from various forestry waste materials, including leaves and branches of *Populus alba* × *P. berolinensis* and *Pinus sylvestris var. mongolica*, exhibit similar effects on these properties. As the quantity of biochar added increases, soil properties such as pH, available phosphorus content, and available potassium content increase to varying degrees, whereas the content of silt-clay aggregates decreases. Furthermore, with regards to biochars produced at different pyrolysis temperatures, the application of biochar pyrolyzed at 700 °C notably boosts soil available potassium and pH levels. Conversely, biochar pyrolyzed at 300 °C significantly increases other physicochemical properties, such as soil ammonium nitrogen content and available phosphorus content. Additionally, in terms of aggregate composition, biochar pyrolyzed at 300 °C can markedly increase the content of soil macro-aggregates and decrease the content of silt-clay aggregates.

Data availability

All data generated or analysed during this study are included in this published article.

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Conceptualization, Q.L.; validation, T.W., L.K., and W.D.; formal analysis, Q.H. and Y.D.; investigation, T.W. and L.K.; writing—original draft preparation, T.W. and L.K.; writing—review and editing, T.W and Q.L.; supervision, Q.L.; project admin-istration, Q.L. and Z.W.; funding acquisition, Q.L. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Sample collection statement

The leaves and branches of *Populus alba* × *P. berolinensis* and *Pinus sylvestris var. mongolica* were collected from Zhanggutai Forest Farm in Zhangwu County, Fuxin City, Liaoning Province, China. This forest farm serves as an experimental base for the Liaoning Academy of Agricultural Sciences. Our sample collection has been permissied by the Liaoning Academy of Agricultural Sciences.

Additional information

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