Species Identification of Palm Leaf Manuscript Based on Py-GC/MS

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Abstract

Palm Leaf Manuscripts (PLMs) are commonly crafted from leaves of the talipot palm (*Corypha umbraculifera*) and the palmyra palm (*Borassus flabellifer*). To identify PLMs made from these two palm species, one chemical marker from the talipot palm and three from the palmyra palm are identified by application of Pyrolysis gas chromatography mass spectrometry (Py-GC/MS). These markers have successfully and been identified in recently manufactured PLMs as well as certain naturally aged PLMs, which indicates that they have specific identification values. The results of principal component analysis (PCA) on selected lignin pyrolysis products reveal a significant difference between the talipot palm and the three groups of the palmyra palm. For the identification of aged PLMs, a combination of the two analytical methods (Py-GC/MS and PCA) is necessary for accurate determination and discrimination of markers. This study provides a solid scientific foundation for determining the source plant species of ancient PLMs.

Introduction

Palm Leaf Manuscript (PLM), known as Pattra in Sanskrit, is one type of classic Buddhist document, written on treated palm leaves with a brush or an iron pen. In China, PLMs are dispersed mainly in Tibet, Yunnan, Hangzhou, among other regions, with the former providing the majority of those recovered. Nearly 300 caskets, with more than 1,000 classical treatises were deposited in the Potala Palace, Norbulingka, and Drepung Monastery in Lhasa of Tibet. These manuscripts contain a number of long-lost Sanskrit original texts, which have been of important historical and cultural value[1], but, due to natural degradation and external environmental factors, these ancient PLMs have gradually deteriorated with the passage of time [2]. This situation underscores the urgent need and task for the conservation and restoration of ancient PLMs.

As early as the Sui Dynasty (A.D. 581–618), ancients realized that plant leaves could be used for making PLMs. In his novel *Daye Shiyiji*(□□□□□), Du Bao recorded some contemporary anecdotes, and, according to this author, Buddhist scriptures were once written on the leaves of Pattra trees[3]. Similar records have also been discovered in a collection of novels, also serving as an ancient encyclopedia. Called as *'Youyang Zazu* (□□□□)*'*, written by Duan Chengshi (803?-863A.D), this collection was written during the late Tang Dynasty, in which were mentioned three types of Pattra leaves that could be selected as the base material for Buddhist manuscripts, allowing for their preservation of five to six hundred years under proper conditions[4] .

Ancient PLMs were traditionally made from the leaves of the species *Borassus* and *Corypha* [5], the majority of which of the palmyra palm (*Borassus flabellifer*) and talipot palm (*Corypha umbraculifera*). The leaves of both species have different physical and chemical properties. Leaves of the former are usually thicker and darker, but also harder than those of the latter. Additionally, manuscripts recorded on palmyra palm leaves aged faster and were more easily and more susceptible to insect or fungal infestations than manuscripts recorded on leaves of the talipot palm [6]. However, simple observation of

these characteristics is not rigorous enough for proper identification of these two palm species. In this circumstance, morphology/anatomy and phytochemical studies must and should be applied to obtain accurate and reliable results, and, thus, a proper and more accurate PLM material identification.

In order to make PLMs, palm leaves must first be processed. The simple procedure allows for better preservation of many of their botanical characteristics and, thus, serves as a solid foundation for the identification of source plant species. According to previous studies, the anatomical structures of the palmyra and talipot palm leaves are different. The cross section of talipot palm leaf reveals a dorsi-ventral structure. Differently, the palmyra palm displays a combination of both dorsi-ventral and iso-bilateral leaf structures[7]. In addition to the cross section, significant differences have also be observed in leaf venation patterns. Freeman et al. compared the leaf venation characteristics of *Borassus flabellifer*, *C. umbraculifera*, and *C. taliera*. Their analysis revealed that the longitudinal and transverse veins of *Borassus flabellifer* met at right angles to each other at the junction, thus forming a brick wall-like structure. In contrast to the palmyra palm, transverse veins of the *Corypha* species branch out from the midrib toward the leaf tip and tend to cross longitudinal veins at acute angles[8].

According to these studies, comparisons of their anatomical characteristics provide reliable results for the proper identification between *Corypha* and *Borassus* species. However, the pre-treatment process of this approach is laborious and requires many samples. Furthermore, it does not cater to the principles of the study of cultural relics, *i.e.*, to be either non-destructive or micro-destructive. Pyrolysis gas chromatography mass spectrometry (Py-GC/MS) technology is widely applied in the detection of organic polymer cultural relics samples[9]. This technology is popular for its simplicity, rapidity, and reliability. It is particularly utilized in the examination of various polymeric materials. This technique involves a pyrolysis process that breaks down organic macromolecules into micromolecules, thus, greatly contributing, especially in this study, to the exploration the molecular-level information of different samples.

Py-GC/MS technology performs well and reliably in the detection of plant materials. Plants secondary metabolic processes are elaborate, and secondary metabolites produced from these processes are typically specific to species. In additionally, since plant species vary in organs, tissues, and growth and development stages, they can consequently be identified and distinguished by Py-GC/MS technology for the characteristics and features cited. At present, this method is widely applied in the identification of ancient paper fibers[10–12].

Lignin is the main component of leaves and essential in the composition in xylem of leaf venation[13] and secondary cell walls[14]. Lignin is mainly formed by the polymerization of three phenolic monomers, such as p-hydroxyphenyl, guaiacyl, and syringyl (abbreviated as H-, G-, S-). The pyrolysis process of lignin formation usually results in the breakdown of ether and C-C bonds, producing a series of relatively simple phenolic compounds. However, most of the phenolic compounds still retain their substitution patterns in the lignin polymer, making it is possible to trace their origin[15].

It has been demonstrated that lignin composition differs in plant species and that its relative abundance differs in softwoods, hardwoods, and grassy plants [16]. Broad-leaf trees are typically abundant in G-, S-lignin[17]. Additionally, the content of H-type lignin, especially p-vinylphenol, is higher in grasses[18]. Several species of fern, such as *Selaginella kraussiana*, *Nephrolepis cordifolia*, and *Pteridium aquilinum*, as well as some gymnosperm plants, like *Cycas revoluta* and *Ephedra fragilis*, differ in terms of their lignin characteristics[19]. Hemp plants contain several types of lignin[20; 21], which cause a display of unique characteristics. Recently, the lignin of four paper samples made of jute (*Corchorus capsularis*), ramie (*Boehmeria nivea*), flax (*Linum usitatissimum*), and hemp (*Cannabis sativa*) were analyzed. Significant distinction in the S/G ratio in the four fibers of the jute paper samples was detected, and the fibers were further analyzed to determine the botanical origins of the ancient paper samples[22].

Identification of plant species by Py-GC/MS technique in past studies has been deemed effective, especially in the analysis of cultural relic fragments and materials. However, to date, this method had not as yet been applied to analysis of PLMs. In this present study, Py-GC/MS is utilized for the first time to identify plant species origins of PLMs.

Materials and methods

In this study's procedure, a batch of leaves from both modern talipot and palmyra palms were first collected to simulate processing experiments in order to obtain standard sample materials. Py-GC/MS were conducted as the analytical technique for the exploration and identification of chemical markers. In order to exclude any processing effects, PLMs recently made in different batches were simultaneously included for analysis. In addition, PLMs aged about 10 years were also included in order to investigate and determine any differences caused by the aging process. Finally, lignin pyrolysis products combined with principal component analysis (PCA) were applied in the differentiation of the two palm species.

Experimental materials

Simulated experimental samples

Regional variations in the traditional process of creating PLMs exist, especially in the strategies of selecting leaves. In southern India and Sri Lanka, unopened leaf buds are typically chosen [23; 24]; in Xishuangbanna of Yunnan Province, in southwestern China, talipot palms of more than 10 years is the optimal choice. Due to the complexity of the principles of secondary metabolic processes of plant development, maturity can be a factor effecting final results. In the present study, three trees of the palmyra palm (*Borassus flabellifer*) and the talipot palm (*Corypha umbraculifera*) of different maturities were selected (Fig. 1). All samples were collected in the Xishuangbanna Tropical Botanical Garden of the Chinese Academy of Sciences. Among these trees, the palmyra palm T1, T3 and talipot palm B1, B3 were fully trees, with thick trunks and broad leaves. Comparatively, the trunk diameters of T2 and B2 were smaller with leaves of narrower width, indicating that they were at a younger level of maturity. Three leaves from each tree were randomly selected for repeat testing and analysis (Table 1).

Table 1
Palm leaves sampling details

Number	Species	Leaf shape	Quantity
T1	Corypha umbraculifera	stiff, broad, thick	3
T2	Corypha umbraculifera	tender, thin	3
T3	Corypha umbraculifera	stiff, broad, thick	3
B1	Borassus flabellifer	stiff, broad, thick	3
B2	Borassus flabellifer	tender, thin	3
B3	Borassus flabellifer	stiff, broad, thick	3

The simulation experiment was conducted in the Dai Cultural Park in Xishuangbanna. The following steps describe the transformation process of fresh leaves to finished products (Fig. 2):

1. Bundling. Leaves from different palms were assigned corresponding numbers. Subsequently, ones from the same palm were tied into individual bundles.

2. Diluting. Groundwater was poured into two iron pots; subsequently, fermented rice water was added to each pot.

3. Boiling. Leaves were put into each of the two pots after the liquid reached a boil. Lemon (*Citrus × limon*) and *Urceola rosea* (*Ecdysanthera rosea*) were then added. The whole boiling process lasted 3 hours.

4. Cleaning. The boiled leaves were untied and the surfaces scrubbed with a towel under running water.

5. Drying. The leaves were dried until their surface became light green or whitish.

6. Storing. The finished products were typically preserved in the form of a scroll, to be later retrieved for inscribing if and when necessary.

Different batches of PLMs

Two different batches of PLMs, made of the talipot palm (*Corypha umbraculifera*) by the local craftsman, were also selected for the present study. The first batch of PLMs was yellowish (Fig. 3a), while the second tended to be greenish (Fig. 3b). These two batches were no more than 1 year in age. Three samples of each batch were selected for repeat testing.

PLMs naturally aged for about 10 years

Aged PLMs were darker than the recently produced PLMs and generally in good condition (Fig. 3c). Both the recent and aged PLMs were stored in the Dai Cultural Park, Xishuangbanna. Furthermore, no

significant differences in production processes existed between those of contemporary PLMs and those aged 10 years. In other words, production procedures of new and old PLMs were relatively identical. Three pieces of the samples were selected for repeat testing as well.

Experimental method

Samples were taken from PLMs with a mass of about 0.5 mg. Subsequently, they were placed in the sample cup and placed into the pyrolyzer (PY3030D, Frontierlab) for pyrolysis at a temperature of 500 ℃. The GC/MS instrument model was QP2030 NX, Shimadz; the inlet temperature was set at 300 ℃ in GC; and the samples were transferred by split injection technique, with a ratio of 20:1. Helium was utilized as carrier gas. NIST Libraries was applied for compound identification. A total of 27 data samples were measured, including 18 samples from simulation experiments and 9 of recently manufactured and aged PLMs.

Principal component analysis (PCA)

Data were standardized by applying SPSS26, followed by PCA. The principal component scores were plotted using Origin2022. A 3D confidence ellipsoid App from Origin2022 App Center was directly used to display 95% confidence interval ellipses.

Results and discussion

Chemical markers of talipot palm (*Corypha umbraculifera*) and the palmyra palm (*Borassus flabellifer*)

Within retention time of 5-20 minutes, the main pyrolysis products of 18 simulated experimental production procedures were: furan, pyran, cyclopentenone, phenol, indole, pyrrole, fatty acid, small molecule aldehydes, ethers, and acids. These products emanate mainly from cellulose, hemicellulose, lignin, proteins, and lipids in palm leaves. Compounds in this region are similar, creating difficulty in distinguishing between the two palm trees species, namely talipot and palmyra.

Within retention time of 20-40 minutes of production pyrolysis products were identified mainly as long chain alkenes, alkanes, fatty acids, mainly from oil and waxes. These substances are quite common in plant leaves, thus still creating difficult in distinguishing the two species. However, a large number of terpenoids and steroids were detected in this region. Because these substances exhibit plant-specificity, particularly the triterpenoid structure compounds [10], in this study, examination of these compounds made it helpful for the identification between the talipot and palmyra palm trees.

A total of 19 terpenoids and steroids were detected in this analysis, including 4 triterpenoids (lupeol derivative 13, 15, 19 and hop-22(29)-en-3-one 18), and six steroids (sitosterol derivative 9, 16; stigmasta derivative 10, 12; cycloergosterol derivative 14; cyclolaudenol 17). Altogether 12 products were detected in both the talipot and palmyra palm trees (1-3, 5-12, 16) (Fig. 4) (Table 2).

Table 2: Assignment of simulation production of talipot palm and the palmyra palm leaves□Similar compounds were detected at different retention time and marked as *.□

No.	RT(min)	Tentative Assignment	Main ions	Fomula	MW
1*-1	20.44	Neophytadiene	70, 82, 97, 123, 154	$C_{20}H_{38}$	278
2*-2	20.53	2-Pentadecanone, 6,10,14-trimethyl-	58, 81, 123	$C_{18}H_{36}O$	268
3*-1	20.52	3,7,11,15-Tetramethylhexadec-2-ene	55, 69, 97, 126	$C_{20}H_{40}$	280
1*-2	20.89	Neophytadiene	70, 82, 97, 123, 154	$C_{20}H_{38}$	278
2*-2	21.26	2-Pentadecanone, 6,10,14-trimethyl-	58, 81, 123	$C_{18}H_{36}O$	268
4*-1	21.33	Phytol	57,71, 97, 123	$C_{20}H_{40}O$	296
3*-2	22.00	3,7,11,15-Tetramethylhexadec-2-ene	55, 69, 97, 126	$C_{21}H_{40}O_2$	324
4*-2	23.21	Phytol	57, 71, 97, 123	$C_{20}H_{40}O$	296
5	25.38	4,8,12,16-Tetramethylheptadecan-4-olide	55, 69, 99, 126	$C_{21}H_{40}O_2$	324
6	29.236	.alpha.-Tocospiro B	57, 83, 125, 137, 153, 402, 419	$C_{29}H_{50}O_4$	462
7	30.2	1,6,10,14,18,22-Tetracosahexaen-3-ol, 2,6,10,15,19,23-hexamethyl-, (all-E)-(.+/-.)-	69, 81, 109, 123, 149	$C_{30}H_{50}O$	426
8*-1	30.64	.beta.-Tocopherol	151, 191, 416	$C_{28}H_{48}O_2$	416
8*-2	31,18	.beta.-Tocopherol	151, 191, 416	$C_{28}H_{48}O_2$	416
9	31.055	.beta.-Sitosterol acetate	57, 81, 105, 147, 381, 396	$C_{31}H_{52}O_2$	456
10	31.05	Stigmasta-3,5-diene	57, 81, 105, 147, 381, 396	$C_{32}H_{48}$	396
11	31.168	dl-.alpha.-Tocopherol	165, 430	$C_{29}H_{50}O_2$	430
12	32.154	Stigmasterol	55, 83, 97, 133, 159, 271, 300, 412	$C_{29}H_{48}O$	412
13	32.32	Lupeol	55, 69, 95, 122, 189	$C_{40}H_{50}O$	426
14*-1	32.402	Cycloergosterol derivative	69, 95, 107, 133, 175, 187, 207, 281, 453		
15	32.444	Lupeol derivative	69, 95, 109, 135, 161, 218, 248,		

			329, 344		
16	32.516	.gamma.-Sitosterol	57, 81, 107, 145, 161, 213, 303, 329, 396, 414	$C_{29}H_{50}O$	414
17*-1	32.695	Cyclolaudenol	69, 95, 109, 135, 161, 175, 300, 353, 379, 407, 422	$C_{31}H_{52}O$	440
18	32.886	Hop-22(29)-en-3-one	69, 81, 107, 135, 161, 189, 221	$C_{30}H_{48}O$	424
17*-2	33.248	Cyclolaudenol	69, 95, 109, 135, 161, 175, 300, 353, 379, 407, 422	$C_{31}H_{52}O$	440
14*-2	33.631	Cycloergosterol derivative	55, 95, 107, 147, 161, 175, 207		
19	34.032	Lupeol derivative	69, 95, 121, 135, 161, 189, 221		
17*-3	34.161	Cyclolaudenol	69, 95, 109, 135, 161, 175, 300, 353, 379, 407, 422	$C_{31}H_{52}O$	440

Cycloergosterol derivatives were detected in the talipot palm at retention time of 32.40 and 33.63 minutes., whereas they were not identified in the palmyra palm samples. In contrast, the samples of the palmyra palm exhibited three types of lone triterpene structural compounds including: lupeol derivative, hop-22(29)-en-3-one, and cyclolaudenol. These substances can, thus, be considered chemical markers for identifying and distinguishing the two species of palm.

However, it is noteworthy that phytol (4) appeared alone in B2, B3. The presence of phytol is highly related to the chlorophyll contained in a plant. Chlorophyll plays an important role in leaves, giving plants their characteristic green color[25]. Chlorophyll exists extensively in tree stems and leaves of plants. Nevertheless, it easily decomposes at high temperatures[26]. The presence of phytol in B2, B3 may be due to insufficient boiling as palm leaves were boiled in a bundled state.

Although characteristic compounds were able to be selected, they were not found in all the leaf samples, especially those of younger maturity. For instance, the cycloergosterol derivative was not detected in B2. Additionally, a significant decline in terpenoids and steroids T2 was observed, indicating the greater influence of maturity on leaf composition, particularly in terpenoids and steroids.

In the production of traditional PLMs, the selection of wider and more mature leaves was emphasized and preferred. However, subjectivity can vary this selection. In order to determine whether these

discrepancies may have had any bearing on the distinction between talipot and the palmyra palms, two distinct batches of PLMs were scrutinized. Analysis results revealed that all three samples from the first batch contained the cycloergosterol derivative (Fig. 5). Similarly, the second batch of PLMs contained the same substance, except in one sample where it was not detected.

In brief, it can be preliminarily determined that the PLMs of the two batches were derived from the talipot palm, a result consistent with actual practice. This study also indicates that the maturity of leaves has an influence on chemical components to some degree, but probably does not affect the final production outcome. Simulation experiments indicate that the use of chemical markers is a reliable method for distinguishing between different species of the origin plants of PLMs.

Compared with the recent PLMs, results from the aged group of samples revealed five newly detected terpenoids and steroids substances, including .γ.-tocopherol, cholesta-4,6-dien-3-ol,(3β), 17.alpha.(H), 21.beta.(H)-Homohopane, diosgeninogen and stigmastera-3,5-dien-7-one (Fig. 6) (Table 4). This indicates terpenoids and steroids vary and occur due to the aging process. However, parts of chemical markers still remained, with cycloergosterol compounds found among them in one sample. Furthermore, no markers of the palmyra palm were found in the three naturally aged PLMs. Therefore, the talipot palm can be preliminarily considered as the source of these PLMs. This result indicates that select chemical markers have exploratory value and utilization in the distinction between the two palms, even with a certain degree of aging.

Table 4: Assignment of terpenoids and steroids of PLMs after approx. 10 years of natural aging

No.	RT(min)	Assignment	Main ions	Formula	MW
1	20.80	2-Pentadecanone, 6,10,14-trimethyl-	58, 71, 109, 124	$C_{18}H_{36}O$	268
2	21.17	3,7,11,15-Tetramethyl-2-hexadecen-1-ol	55, 82, 96, 123	$C_{20}H_{40}O$	296
3	25.66	4,8,12,16-Tetramethylheptadecan-4-olide	57, 71, 99	$C_{21}H_{40}O_2$	324
4	29.56	.α.-Tocospiro A	57, 71, 109, 137, 153, 191, 205, 237, 402, 419	$C_{29}H_{50}O_4$	462
5	30.94	.gamma.-Tocopherol	57, 71, 123, 151, 191, 416	$C_{28}H_{48}O_2$	416
6	31.23	Cholesta-4,6-dien-3-ol, (3.beta.)-	57, 81, 119, 135, 149, 394	$C_{27}H_{44}O$	384
7	31.37	.beta.-Sitosterol acetate	57, 81, 105, 147, 175, 213, 255, 288, 381, 396	$C_{31}H_{52}O_2$	456
8	31.48	dl-.alpha.-Tocopherol	57, 71, 121, 165, 177, 205, 430	$C_{29}H_{50}O_2$	430
9	31.74	17.alpha.(H),21.beta.(H)-Homohopane	69, 95, 109, 137, 163, 191, 205	$C_{31}H_{54}$	426
10*-1	31.89	Cycloergosterol derivative	55, 95, 107, 123, 166, 189, 203,229		
11	32.45	Stigmasterol	55, 83, 97, 133, 159, 271, 300, 412	$C_{29}H_{48}O$	412
12	32.69	Diosgenin	69, 79, 97, 139, 159, 271, 282	$C_{27}H_{42}O_3$	414
13	32.82	.gamma.-Sitosterol	57, 81, 105, 145, 163, 213, 231, 255, 303, 329, 381, 396, 414	$C_{29}H_{50}O$	414
14	33.44	Stigmasta-3,5-dien-7-one	55, 91, 109, 174, 269, 410	$C_{29}H_{46}O$	410
10*-2	33.59	Cycloergosterol derivative	55, 69, 95, 107, 133, 149, 175		

Principal component analysis (PCA)

The palmyra and talipot palms were basically similar in terms of pyrolysis products during retention time within 5-20 minutes. However, this reveals different relative amounts of the products, particularly those originating from lignin. This presented the opportunity to distinguish between the two palm species through lignin product analysis. S-type and G-type lignin products were selected for analysis. Ten

pyrolysis products derived from lignin compounds with more stable peaks were finally selected (Fig. 7). All the above 27 samples were subjected to PCA analysis.

From factors 2 and 3 score plots (Fig. 8a), all but one talipot data is observably well differentiated from the palmyra palm group. The palmyra palm group scores mainly fell in Quadrant IV, while the talipot data scores basically appeared in Quadrants I and III. PC2 scores of the palmyra palm group and the talipot group differed significantly. Scores of the palmyra group were all positive, while the talipot one generally scored low. Aged PLMs were substantially more akin to the talipot palm and correctly grouped.

Plots of the three principal components 3D scores and their 95% confidence intervals (Fig. 8b) show that the two confidence ellipses overlapped at a low rate. Moreover, all the data fell within the self-squared confidence intervals.

Thus, 10 lignin selected pyrolysis products combined with PCA can effectively differentiate plant source of PLMs (Fig. 7). Additionally, this process can even be useful in the identification of PLMs with a certain degree of aging. This method seems to perform better in distinguishing species and possibly relates to properties of lignin. Presence of lignin displays higher stability, slower rate of natural degradation [27-31], thus, more capable in maintaining original characteristics under different situations and conditions.

PC2 in Fig. 8a displays the significant difference between the palmyra palm and talipot palm. All the scores in the palmyra groups are positive, while negative for most of the talipot group. Additionally, it is notable that S8 and G1 are furthest away on the PC2 axis (Fig 9). This indicates that these two variables are the main factors affecting PC2 score. Consequently, the differences between PLMs made from the talipot palm and the palmyra palm are mainly dependent on variation of o-Guaiacol (G1) and Acetosyringone (S8).

In terms of PLMs being recently produced, both chemical markers and PCA show reliable results for distinguishing the two palm species. Palmyra palm markers, including lupeol derivative, hop-22(29)-en-3-one, and cyclolaudenol, were not found in all aged PLMs. On the other hand, the cycloergosterol derivative was detected in only a few of the aged PLMs. Aging could, thus, be a possible factor for the absence of chemical markers in certain samples. In this situation, PCA analysis yielded positive outcomes in discriminating PLMs. Hence, for aged PLMs, both PCA and chemical marker identification techniques for a more accurate assessment are strongly recommended.

Conclusion

In the present study, Py-GC/MS and multivariate statistical analysis were applied to differentiate between different plant species in the production of PLMs. Aside from the products of the simulating experiments, both recently manufactured groups of PLMs and aged groups of PLMs were also selected for analysis. The findings provide a new reference for identifying the plant origin of ancient PLMs.

Through Py-GC/MS analysis, this study also reveals that processed leaves from the talipot palm (*Corypha umbraculifera*) contain a cycloergosterol derivative. In contrast, palmyra palm leaves contain three lone compounds, viz. lupeol derivative, hop-22(29)-en-3-one, as well as cyclolaudenol. These compounds can possibly be employed as chemical markers to distinguish between newly produced and aged PLMs origin plant species. However, since a chemical marker was only detectable in portion of the aged samples, it was deemed necessary to combine the PCA to assist in origin discrimination. Three principal component factors were successfully extracted. The PCA results displayed a good differentiation between the palmyra and talipot palm groups.

Declarations

Author Contribution

Conceptualization, data analysis, writing-original draft preparation, QC; the simulation experiment QC, HJ; instrument provision YY, HB; writing-review and editing, HJ, HB, YY. All authors have read and agreed to the published version of the manuscript.

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Figures

Figure 1

a) *Corypha umbraculifera* (leaves more spread and broader); b) *Borassus flabellifer*(leaves narrower and tougher); c) *Corypha umbraculifera* petiole (embedded in the form of a cross shape); d) *Borassus flabellifer* petiole (stout, crisscrossed, with toothed thorns on margins).

Figure 2

Simulation experiment process - a) Bundling; b) Diluting; c) Boiling; d) Cleaning; e) Drying; f) Storing

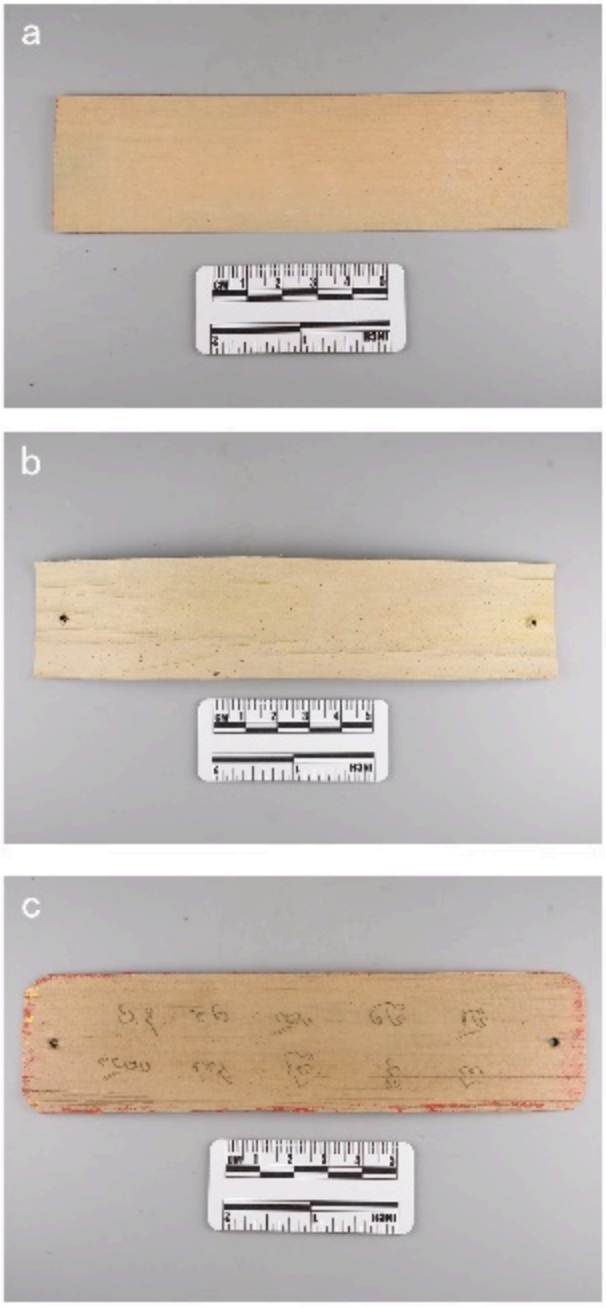


Figure 3

Recent and aged PLMs - a) the first batch; b) the second batch; c) aged group

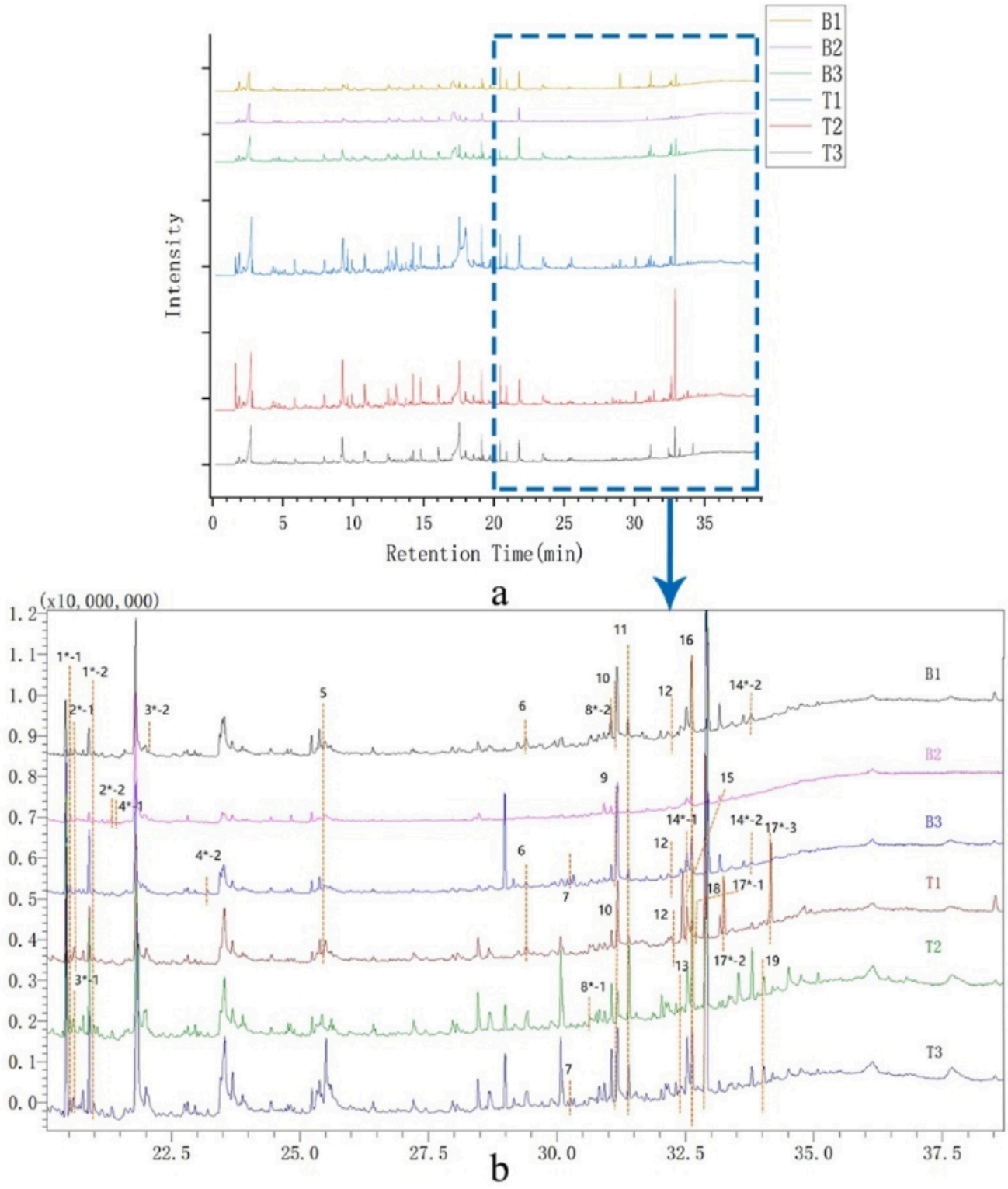


Figure 4

Talipot palm and the palmyra palm pyrolysis products - a) TIC profiles; b) Retention time of 5-20 minutes. terpenoids and steroids in talipot and the palmyra palm leaves

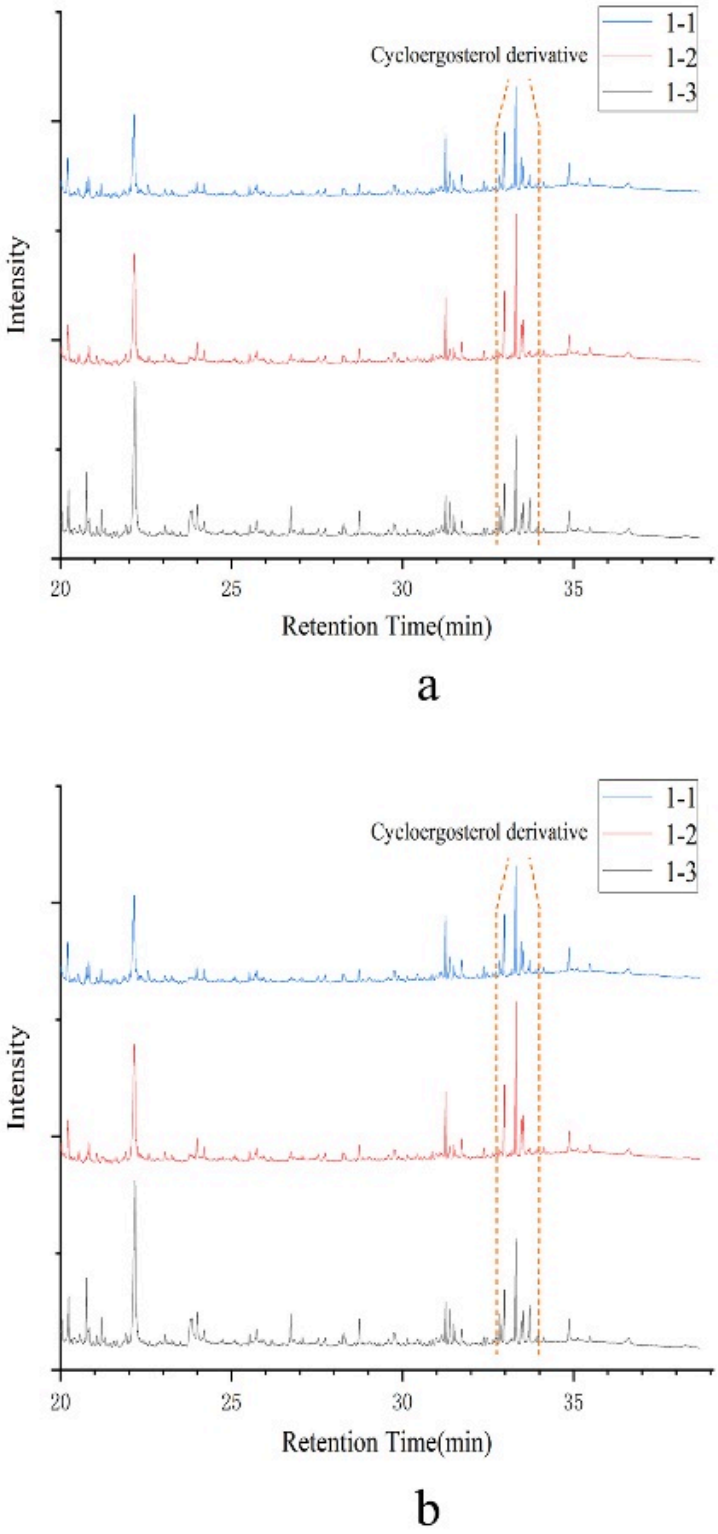


Figure 5

a) the first batch; b) the second batch

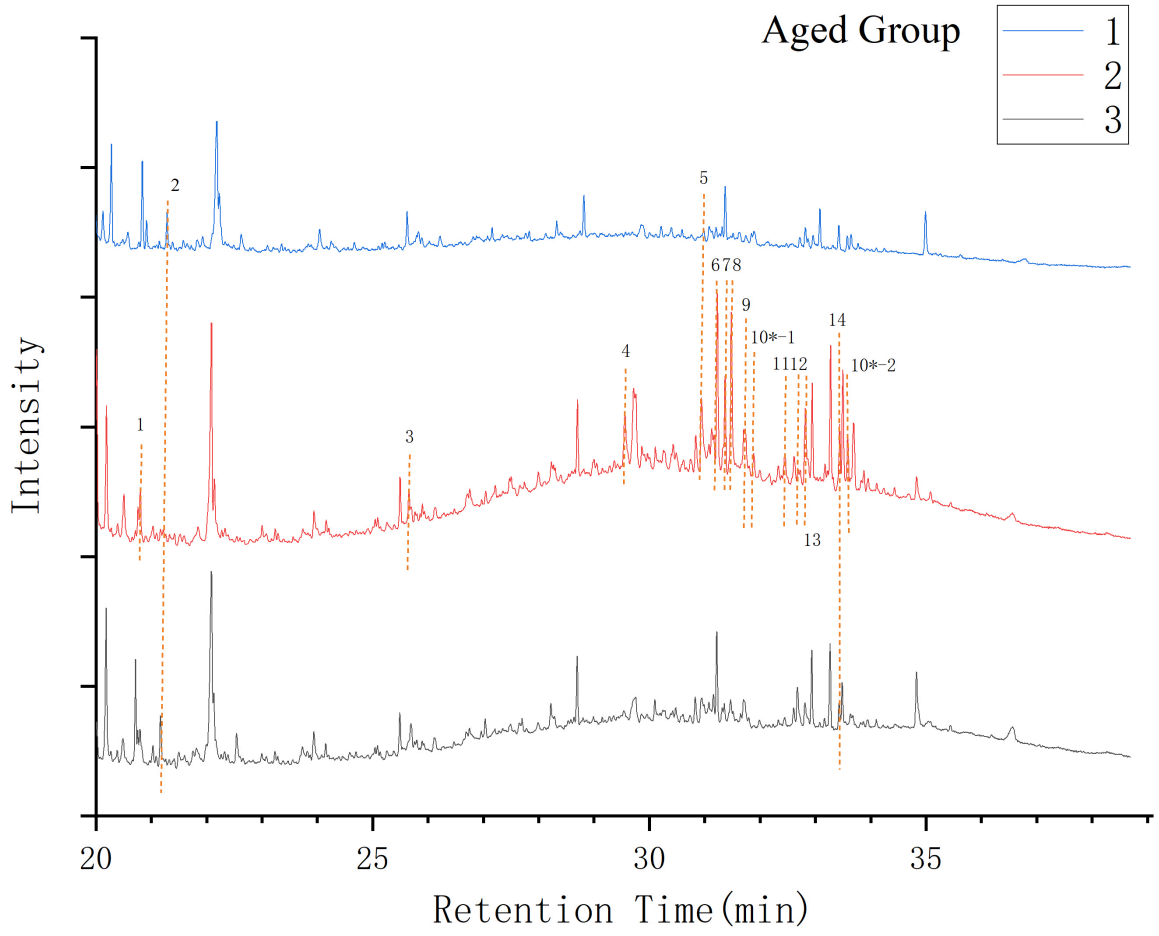


Figure 6

TIC of aged group

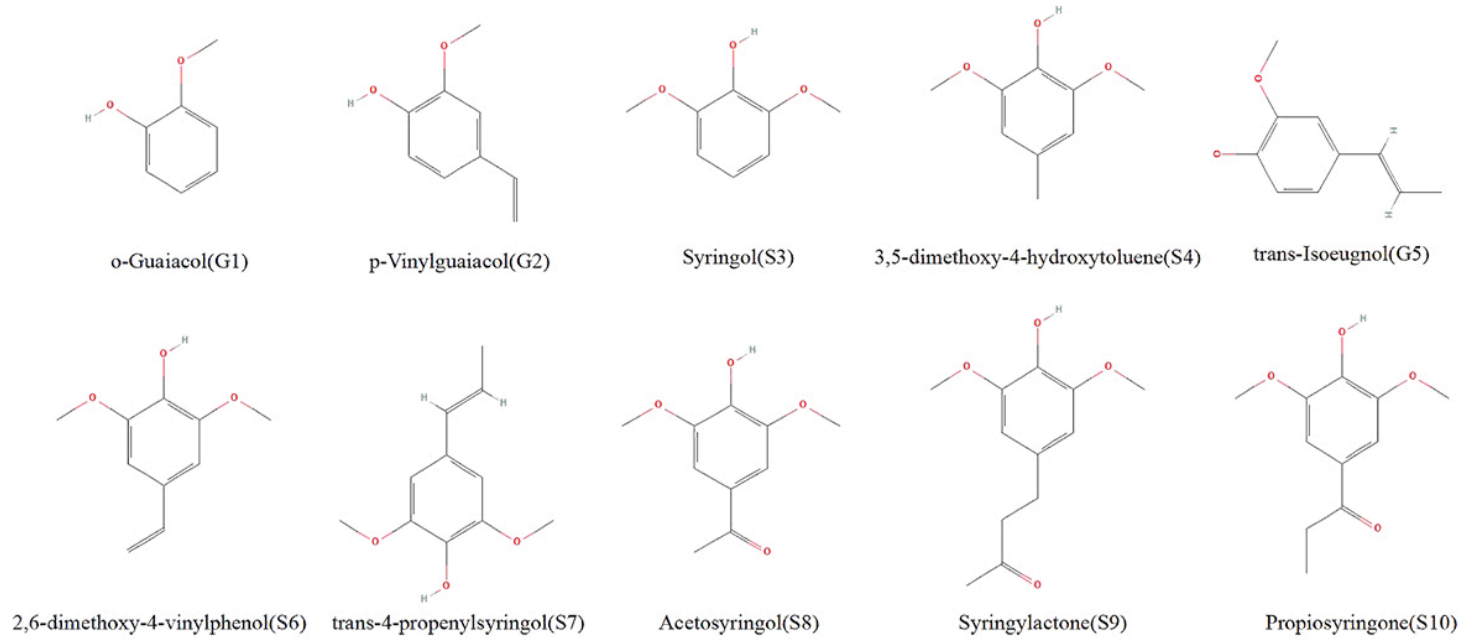
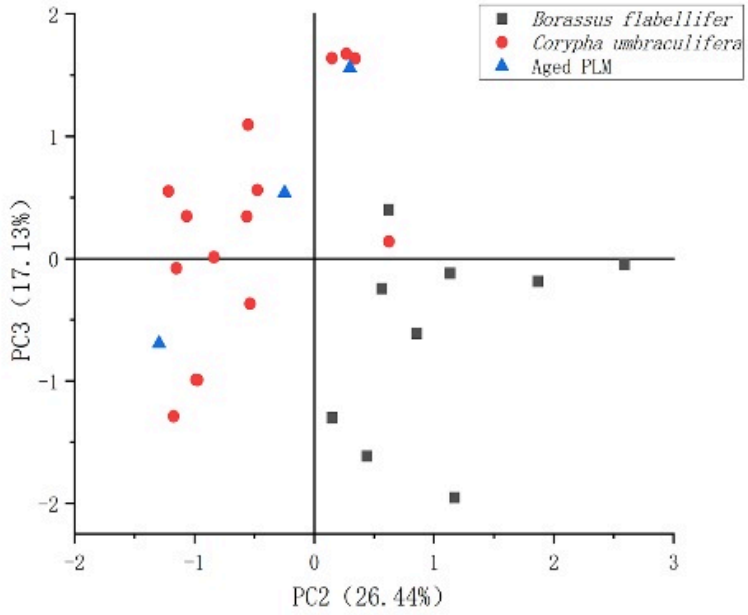
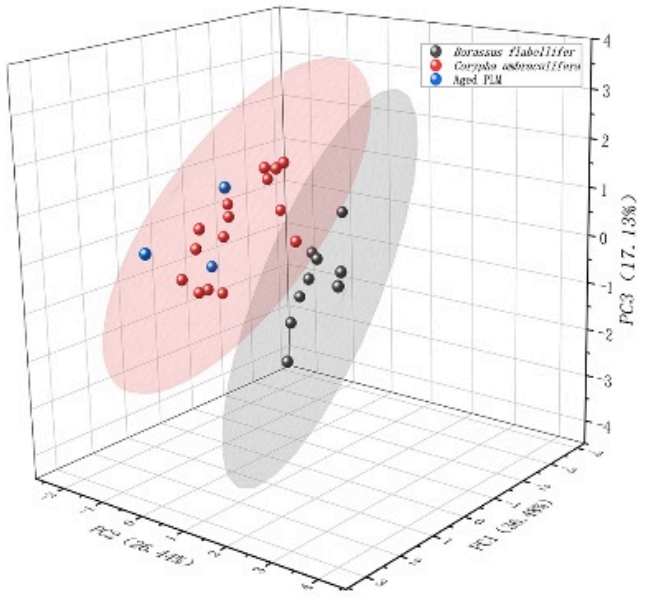


Figure 7

Ten lignin pyrolysis products



a



b

Figure 8

a) Score plot of PC2 and PC3 scores; b) Score plot of three principal components scores)

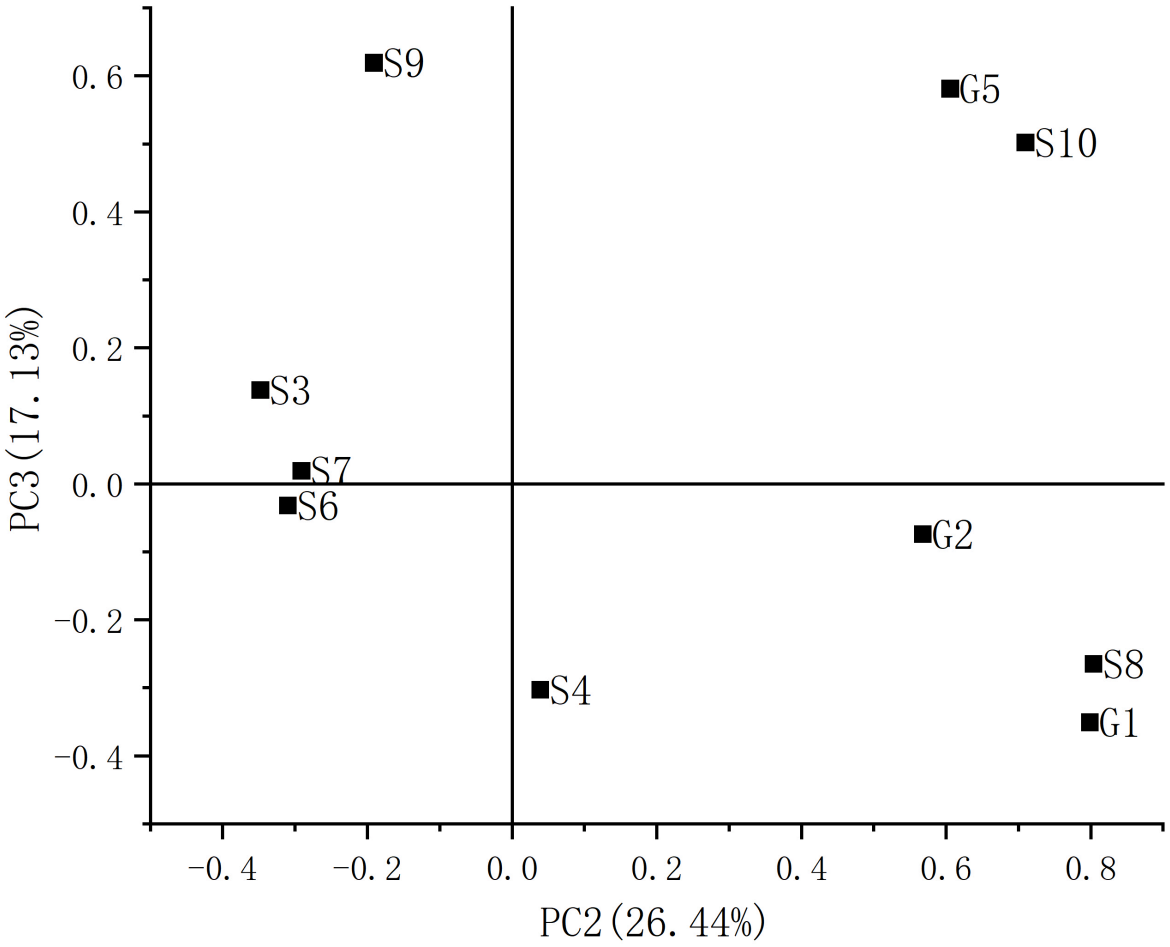


Figure 9

PC2 and PC3 loading map