



Assessment of the relationships between extractive content, mould growth, and drying methods of Scots pine wood using multivariate data analysis

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Abstract

Wooden construction material is a sustainable contribution to carbon sequestration and long-term storage. Despite its strength, sustainability and versatility, the vulnerability to biodeterioration is an issue. Therefore, this study aimed to identify the differences in mould growth features and surface extractive composition of the Scots pine (*Pinus sylvestris* L.) sapwood sideboards between air- and kiln-drying methods using multivariate data analysis. Air and kiln-dried sideboards were used to extract different low molecular compounds from the surface layer, assess the moisture content, and conduct a mould test. Principal component analysis revealed the grouping of the drying types. This was confirmed by partial least-squares discriminant analysis, which allowed the sideboard characteristics of the two wood drying types to be described. An outlier was detected among the air-dried observations. The collected data show more intensive mould growth on kiln-dried Scots pine sideboards than on air-dried ones. Higher amounts of total lipophilic compounds, phenols and inorganic components were found on the kiln-dried sideboard surface. Also, surface extractives from kiln-dried sideboards contained higher amount of almost all analysed fatty and resin acids, except for the oleic acid, which was more prevalent on the air-dried sideboard surface. Low-molecular-weight sugars, namely glucose, saccharose and fructose, were present in significant amounts on the surface of the kiln-dried sideboards. This has presumably contributed to the rapid spread of mould. In general, multivariate modelling allowed to establish that the method of wood drying significantly influenced the redistribution of extractive components on the surface and the subsequent mould growth.

1 Introduction

Mould growth is undesirable in wood construction because it is associated with aesthetic issues, increased maintenance costs, and poses a health hazard (Platt et al. 1989). The mould includes various species of fungi that cause wood discolouration due to the growth of their biomass on the surface. Although mould does not change the mechanical properties of wood, it is necessary to treat the material to prevent mould development through chemical and thermal wood modification or wood coating (Sheikh et

al. 2013; Niemz et al. 2023). Mould growth on wood surfaces depends on many factors, such as local climate conditions (temperature, relative humidity, etc.), geographical location, fungal diversity, moisture content and extractive content of the wood (Terziev and Boutelje 1998; Råberg et al. 2005; Poohphajai et al. 2023). Among these factors, the content of wood extractives demonstrates significant practical interest. In addition to cellulose, hemicelluloses, and lignin as the main structural components, wood contains various non-structural low molecular weight compounds that can be extracted using appropriate solvents (Fengel and Wegener 1984; Sjöström 1993). The waxes, fats, terpenes and terpenoids, saturated and unsaturated fatty acids, monosaccharides and complex carbohydrates, alkanes, proteins, alkaloids, phenolic compounds and flavonoids refer to wood extractives (N'Guessan et al. 2023). However, the qualitative and quantitative characteristics of the various components vary significantly in different wood materials. This is directly related to the tree species, age, geographical

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location, and climate conditions during its growth. Seasonal characteristics of tree cutting and wood material storage time also significantly impact extractive composition (Terziev et al. 1997; Silverio et al. 2011). In addition, the qualitative profile of the extractive components is so unique that it allows for creating a unique “chemical signature” for identifying wood material through belonging to a specific family, genus and wood species (N’Guessan et al. 2023). In general, extractives provide a physical and chemical barrier against wood-degrading agents. The composition of extractives affects many physical properties and, to a lesser extent, mechanical properties of wood, namely colour, odour, water permeability, durability, density and hardness, and acoustic properties (Pettersen 1984; Santana et al. 2010; N’Guessan et al. 2023). Also, the protective properties of certain extractives against fungal, bacterial and insect agents have been proven (N’Guessan et al. 2023). It was found that lignivorous organisms (fungi and termites) destroyed wood from which extractives had previously been removed much faster than unextracted wood (Kirker et al. 2013). The biocidal properties of wood extractives could be used in developing preparations for preserving the natural durability of wood (Lovaglio et al. 2017).

Since extractives are complex mixtures, their composition can vary depending on the extraction method chosen (Diouf et al. 2009) and the application of various technological operations such as drying. The wood is dried to remove water and produce a lighter, more durable and stable material. Drying together with heat treatment not only causes a change in the physical and mechanical properties of wood but also causes a change in the composition of extractives and their distribution in the wood layers (Schlstedt-Persson and Wamming 2010).

Scots pine (*Pinus sylvestris* L.) wood, as one of the main sources of wood constructions in Nordic countries, is rich in extractives, which significantly affects the final material’s properties during wood processing (drying, modification, heating, etc.). Given the susceptibility of Scots pine wood to mould (Schlstedt-Persson et al. 2011; Sheikh et al. 2013), it was chosen for this study.

Given all of the above, the composition of extractives and their influence on the growth of pathogenic organisms, particularly mould fungi, is an important issue for the wood industry and requires detailed investigation. In this study, we hypothesise that kiln drying leads to a greater susceptibility to mould growth due to the surface redistribution or concentration of specific extractives. To confirm this, the effects of air- and kiln-drying methods on the composition of selected surface extractives in Scots pine sideboards were assessed, and their relationship with mould growth characteristics was analysed using multivariate data analysis.

2 Materials and methods

2.1 Sample preparation and drying

A total of 20 Scots pine sideboards were analysed. The sideboards were obtained initially from 10 Scots pine trees cut and sawn in a Sawmill in Norrbotten County (Sweden). Each board had dimensions of 25 mm tangential (T) × 100 mm radial (R) × 220 mm longitudinal (L) and contained only sapwood. No permits were required for this study as no protected or endangered species were used.

Two wood-drying methods were used in the study: air- and kiln-drying. Ten randomly selected Scots pine sideboards were single-stacked and dried indoors on stickers for 30 days at a temperature of 20 °C and RH of about 10%. The other 10 sideboards were dried in a laboratory kiln (Valutec, Sweden) with air circulation. During kiln drying, the sideboards were placed in pairs, and the sapwood sides of each pair were blown with air. This resulted in a rapid movement of water and moisture from the deep layers of the wood to the wood surface. Drying was carried out for 44 h, including a heating phase (1.7 h), the main drying phase (37.3 h) and a cooling phase (5 h). The drying temperature was 60 °C and rose to 77 °C during the drying phase (Myronycheva et al. 2018). The conditioning phase was excluded from the kiln drying process to eliminate its influence on the distribution of extractive components on the board surface.

2.2 Analysis of extractive content

Planing of the surface of wooden sideboards (0.25 mm depth) from the bark side of sapwood from 10 air-dried sideboards and 10 kiln-dried sideboards was done to obtain the material for extraction of lipophilic and water-soluble compounds. The planed surface wood from each board was separately milled in a planetary mill (Fritsch, Germany). The resulting material was stored at – 20 °C. The milled wood (0.5 g) was used to determine the moisture content by heating it in an oven at 103 °C according to the standard SS-EN 13183-1 (2004).

Extractives were extracted from 1.0 g of milled surface wood with acetone (VWR Chemicals: 20165.323) in a Soxhlet extractor as described in SCAN-CM 49:03 (2003) standard method. After acetone evaporation and drying of the residue, the total extractives content was measured in mg/g of dry mass.

The content of total phenols (mg/g of dry mass) was evaluated using the Folin-Ciocalteu (FC) approach (Julkunen-Tiitto 1985) with tannic acid (VWR Chemicals; 83510.260) as a standard. After adding all components to the sample, the absorption was measured after 40 min at 735 nm in a UV spectrophotometer (U-1500, Hitachi, Japanese).

Saturated (palmitic and stearic), unsaturated (oleic and linoleic) fatty acids and resin (pimaric, isopimaric, abietic and dehydroabietic) acids and glycerol were measured in the dried acetone extracts using a Gas Chromatography-Mass Spectrometry (GC-MS) system (GCMS-QP2020, Shimadzu, Japan) with A SUPELCO SLB-5 MS capillary column (30 m, 0.25 mm inner diameter, 0.25 µm film thickness). Before GC-MS, trimethylsilylation was done by treatment with 100 µl of N, O-bis-(trimethylsilyl)trifluoroacetamide (BSTFA) and 50 µl of trimethylsilyl chloride (TMSCl) in an oven at 70 °C for 20 min (Sjostrom and Alen 1999) with 1-methylnaphthalene dissolved in pyridine as internal standard (Lai 1992). The oven temperature program used a heating rate of 10 °C/min starting from 100 °C (1 min at initial temperature) to 270 °C (holding for 2 min. at final temperature). The analysis cycle took 25 min, and the mass spectrum was recorded at 70 eV in 40–500 m/z with a scan speed of 1000. NIST Mass Spectral Library was used to identify fatty and resin acids (Johnson 2014). Quantification was performed by comparing the target peak area with the peak area of the internal standard.

The low molecular weight sugars (saccharose, glucose and fructose) in the water extracts were analysed by High-Performance Liquid Chromatography (HPLC) (Shimadzu, Japan) with Hi-plex Pb-column (250 mm length, 7.7 inner diameter, 8 µm particle size) (Karlsson et al. 2012). Water extracts were previously made by mixing the wood with water, followed by an ultrasonic treatment for 1 h, and then left overnight. Water extracts were filtered (50 µm) and analysed in HPLC at 60 °C using water as eluent with 0.3 mL/

min flow rate. An RI detector was used to detect sugars, and quantitative values were determined by comparing them with calibration curves for target compounds.

The amount of nitrogen was investigated as described in Kjeldahl (1883). The ash content was determined by thermogravimetric analysis using a hardening furnace (N7, Nabertherm, Germany). All measurements of extractive compounds are presented in mg/g of dry mass.

Microsoft Excel software was used to calculate the minimum, mean, maximum and confidence interval (CI) for each variable, namely the 'MIN', 'AVERAGE', 'MAXIMUM' and 'CONFIDENCE' functions. More detailed data are presented in Table 1.

2.3 Mould test

Ten air-dried and ten kiln-dried Scots pine sideboards were investigated in this study. Mould growth on the planed board surfaces was induced by the spraying of a water mixture which contained spore suspension of the five fungal species (*Aspergillus niger* van Tieghem, *Penicillium commune* Trom, *Paecilomyces variotii* Bainier, *Mucor plumbeus* Bonord and *Triphoderma longibrachiatum* Rifai). All fungal cultures belong to the Division of Wood Science and Engineering collection at Luleå University of Technology (Skellefteå, Sweden). Fungal cultures were grown in Petri dishes (Ø 90 mm) using malt extract agar medium (Milipore; 70145) in the laboratory chamber (HPP260eco, Memmert, Germany) at 25 °C and RH of 90% for 7 days. The dilution buffer (10 mL) (0.02 M Potassium dihydrogen

Table 1 Minimum, mean, maximum and confidence interval (CI) of extractive components obtained from air- and kiln-dried Scots pine sideboards. The data was previously reported in Karlsson et al. (2017)

Name of component	Air-dried				Kiln-dried			
	Minimum (mg/g)	Mean (mg/g)	Maximum (mg/g)	CI ^b	Minimum (mg/g)	Mean (mg/g)	Maximum (mg/g)	CI ^b
Total extractives	25.16447	34.9178 ^a	49.06973	± 5.464453	41.86167	57.0666	69.70297	± 5.060975
Palmitic acid	0	0.265201 ^a	1.771422	± 0.375986	0	0.268747	1.254856	± 0.282816
Oleic acid	0.488388	1.254339 ^a	2.458674	± 0.403495	0	0.200793	1.77299	± 0.339039
Linoleic acid	0	0.06059 ^a	0.150412	± 0.032616	0	0.200793	0.484073	± 0.09916
Stearic acid	0.086986	0.223717 ^a	0.530558	± 0.09642	0	0.325746	1.249394	± 0.210705
Pimaric acid	0.381058	1.007886 ^a	2.153737	± 0.381639	0.111469	1.94274	3.770454	± 0.786322
Isopimaric acid	0.282911	0.791294 ^a	1.67307	± 0.330812	0.102333	1.492612	3.132764	± 0.689876
Dehydroabietic acid	0.778021	2.894875 ^a	6.574356	± 1.099339	0.324956	4.549238	7.584099	± 1.516302
Abietic acid	0.246364	0.446088 ^a	0.941347	± 0.158342	0.331476	0.854376	2.245718	± 0.360825
Glycerol	0.123983	0.425187 ^a	1.054243	± 0.177934	0	0.815225	1.67847	± 0.324571
Total phenols	0.221447	0.402826 ^a	0.791817	± 0.123763	0.006388	0.808393	2.063208	± 0.360428
Nitrogen	0.032927	0.400752 ^a	2.47457	± 0.514712	0	0.267047	0.697599	± 0.175163
Saccharose	0.066026	0.088536 ^a	0.146079	± 0.015894	0	0.416249	1.710012	± 0.309742
Glucose	0.053393	0.176142 ^a	0.467799	± 0.104458	0	0.805327	1.827902	± 0.384497
Fructose	9.51E-05	0.14627 ^a	0.702911	± 0.147858	0	0.602831	2.475419	± 0.481553
Ash	0.179372	0.310669 ^a	0.394391	± 0.05836	0	0.805689	1.851852	± 0.346188

^aCounted for nine observations (without board AD2, which had extremely high values of resin and fatty acids and later excluded from analysis)

^bThe significance level $p=0.05$

phosphate (VWR Chemicals; 7778.77.0), 0.05 M Disodium hydrogen phosphate dehydrate (Merck KGaA; 10028.24.7), 0.074 M Sodium chloride (Sigma Aldrich; 7647.14.5), 0.01% (v/v) Tween 80 (VWR Chemicals; 9005.65.6), 1 L distilled water) was used to wash the spores from the surface of each Petri dishes separately. Spores from hyphae were removed into the dilution buffer using a sterile glass spreader. The spore suspension was filtered through sterile mineral wool to remove residual mycelium parts. The number of spores was counted using a hemocytometer, and the suspension was diluted to a concentration of 10^6 spores/mL. Equal volumes of spore suspensions of five fungal cultures were mixed and stored at 4 °C until use. The resulting suspension (2 mL) was sprayed on each Scots pine board, and sideboards were left in the laboratory chamber (HPP260eco, Memmert, Germany) at 22 °C and RH of 90% for 30 days.

ImageJ (NIH, Maryland, USA) software determined the percentage of mould coverage on the board surface by image analysis of all board sides. The mould class was determined according to the method described by Sehlstedt-Persson et al. (2011) and Myronycheva et al. (2019). The assessment of mould growth on the sideboard surfaces was conducted by two researchers in a laboratory environment, independently of each other. No additional data, including the method of drying the boards or the composition of the extractives from the surface, were provided to the researchers prior their assessments. To establish the class of mould, the researchers used the descriptions given in Table 2. The spread, density, and colour intensity of mould on wood surfaces were visually assessed. Through visual assessment of all sides of the sideboards, each sample was assigned a mould growth intensity class (0–6). If there was no visible mould growth, the sample was assigned class 0. In the case of the most

intensive mould growth, the sample had the highest class 6. There was consistency in the results obtained during the assessment process from both researchers.

2.4 Principal component analysis (PCA) and partial least-squares discriminant analysis (PLS-DA)

As a result of the analysis of the composition of extractives, moisture content and the mould test, a dataset containing 20 observations and 20 variables was obtained. The SIMCA 18 (Sartorius AG, Göttingen, Germany) software package was used for PCA and PLS-DA modelling, aiming to describe the differences in mould growth features and extractive composition of the sideboard surface between the two wood drying methods (air- and kiln-drying). PCA was used to overview the correlation pattern, and PLS-DA was used to describe the sideboard characteristics for the two wood drying types. Cross-validation was used to test the robustness and interpretability of the models. External validation of the PLS-DA models was not performed due to the small dataset limited to only 20 observations. Prior analysis, all variables were scaled to unit variance.

3 Results and discussion

3.1 Investigation of extractive content and mould growth features

A quantitative evaluation of 16 extractive components from 10 air-dried sideboards and 10 kiln-dried Scots pine sideboards was conducted. The minimum, mean, and maximum values of each compound are given in Table 1. The data obtained for each wood sample were used for further multivariate analysis using PCA and PLS-DA.

Examples of mould growth on the surface of the boards after a 30-day mould test are shown in Fig. 1. The percentage of mould surface coverage and mould class were determined by visual inspection. As seen in Table 3, more intensive mould growth was detected on the surfaces of the kiln-dried boards. As many as 7 out of 10 kiln-dried samples were completely covered with mould (90–100%), and 9 kiln-dried boards were assigned the highest class 6.

At the same time, significantly less mould growth was observed on the air-dried sideboards. Half or less than half of the surface (5–50%) was covered with mould for 8 out of the 10 air-dried samples analysed. The determined class for mould on the air-dried sideboards was lower than on the kiln-dried sideboards (class 4 and lower for 7 samples). The average moisture content of the sideboards after air- and kiln-drying was 4.6% and 4.4%, respectively. Detailed data for each wood sample are presented in Table 2.

Table 2 Classes for assessment of mould growth on wood surfaces

Mould class	Description
0	No visible mould growth on the surface
1	Initial fungal growth consisting of scattered hyphae on the surface, some doubt that it is not quite free from mould
2	Still scattered mould growth, but more apparent than in 1. Conidiophores may have started to develop, no doubt that there is mould, but on a small scale
3	Moderate mould growth, patchily distributed, mould found in more coherent strings and as black and colored spots and islands, and hyphae with developed conidiophores
4	Heavy growth over the entire surface, sideboard surfaces are covered with fluffy mycelia and spores (viewed from the side)
5	Very heavy mould growth, sideboard surfaces are covered with fluffy mycelia and multicoloured spores
6	Extremely heavy mould growth with intensive multicoloured sporulation

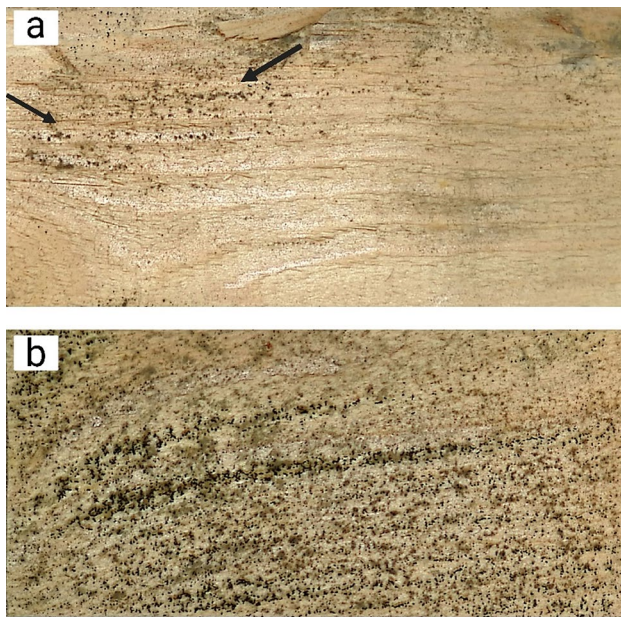


Fig. 1 Examples of surfaces of air- (a) and kiln-dried (b) Scots pine sideboards covered by mould after a 30-day mould test. The arrows mark the mould growth area on the air-dried board. The kiln-dried board is completely covered in mould

Table 3 Mould area and class on air- and kiln-dried Scots pine sideboards after a 30-day mould test. The moisture content was measured before the mould test. The data was previously reported in Karlsson et al. (2017)

Board ID	Drying type, (Air/Kiln)	Moisture, (%)	Mould area, (%)	Mould class
AD1	Air	5.9	60	4
AD2	Air	4.7	5	2
AD3	Air	4.8	30	5
AD4	Air	3.7	45	4
AD5	Air	4.5	100	4
AD6	Air	3.8	5	6
AD7	Air	10.7	20	4
AD8	Air	3.5	50	4
AD9	Air	5.6	5	3
AD10	Air	4.4	50	6
KD1	Kiln	5.0	90	6
KD2	Kiln	4.3	50	4
KD3	Kiln	6.2	60	6
KD4	Kiln	4.5	100	6
KD5	Kiln	3.5	100	6
KD6	Kiln	2.0	100	6
KD7	Kiln	2.7	100	6
KD8	Kiln	4.5	90	6
KD9	Kiln	4.0	70	6
KD10	Kiln	6.5	100	6

3.2 Principal component analysis

PCA was performed to get an overview and identify correlation patterns between the type of wood drying, the mould growth and the resulting composition of extractives on the dried wood surfaces. PCA is a linear approach that allows the visualisation of such data by creating linear combinations of the original variables onto principal components in plots and histograms. In this way, differences and similarities between samples become highlighted.

The result of the PCA analysis of the entire dataset is shown in Fig. 2a, b. The systematic variation in the dataset was summarised by two significant principal components explaining 57.7% of the total variability ($R^2[1]=0.349$ and $R^2[2]=0.228$). The resulting two components are interpretable and visually clear, a clustering of observations by type of sideboard drying is present.

In the score plot (Fig. 2a), the observations are coloured by the type of sideboard drying (air- and kiln-dried). The two drying types separated well and show a difference between the surface extractive composition and mould growth dependency, which is reflected in the loading plot (Fig. 2b). The data has one clear outlier, AD2, seen in the score plot Fig. 2a. The reason for AD2 being a strong outlier is seen in Fig. 3, where its data is compared to the rest of the air-dried sideboard observations. AD2 data compared to all the other air-dried sideboards show that it has extreme values on almost all fatty and resin acids. Linoleic, oleic, pimaric, dehydroabietic and abietic acid values were considerably higher for the AD2 than for other observations in the air-dried group. The data collection procedure was followed up, but the reason for such extreme values could not be verified. Thus, it is still unclear whether this strong divergent behaviour results from a measurement error or if AD2 is a unique and extreme observation. A sign of a strong outlier is when the first principal component is oriented towards the outlier and as in our case explains the difference between AD2 and the other observations. Hence, the outlier AD2 was excluded from further analysis.

A second PCA model without AD2 observation can be seen in Fig. 2c, d. The model explains 52.6% of the variations in the data ($R^2[1]=0.369$ and $R^2[2]=0.156$). In the score plot (Fig. 2c), the observations are again positioned rather well in two groups, following the type of wood drying. One air-dried sample, AD10, is more grouped within the kiln-dried type group. However, in the previous PCA model, it was also closely localised with the kiln-dried group. The grouping of observations shows a difference between the drying types regarding the chemical composition on the board surfaces in the data presented. In the loading plot (Fig. 2d), it can be seen that kiln-dried samples are associated with having higher values on the variables to the

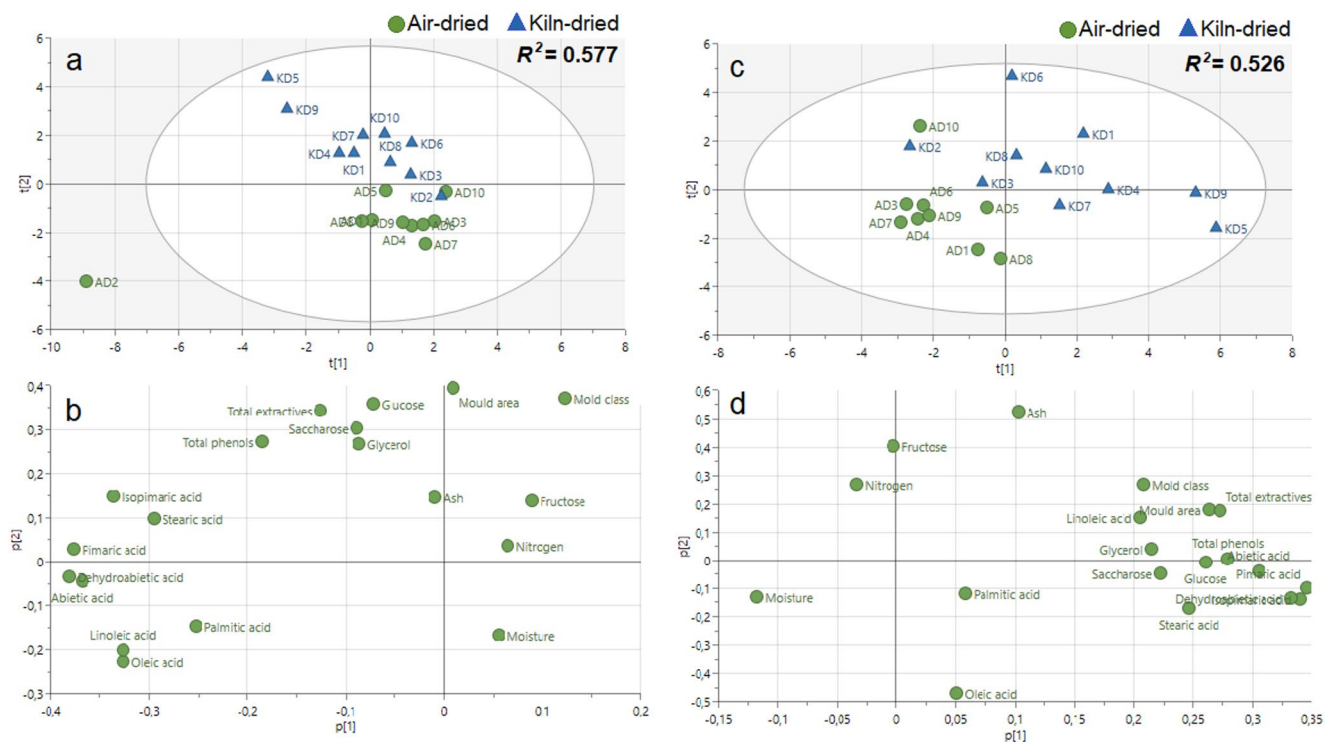


Fig. 2 PCA score plots (a, c) and loading plots (b, d) of components 1 and components 2 for two types of Scots pine wood drying. The first PCA model (a, b) contains 20 observations (10 air-dried and 10

kiln-dried), the second (c, d) – 19 observations (AD2 observation was excluded from the model)

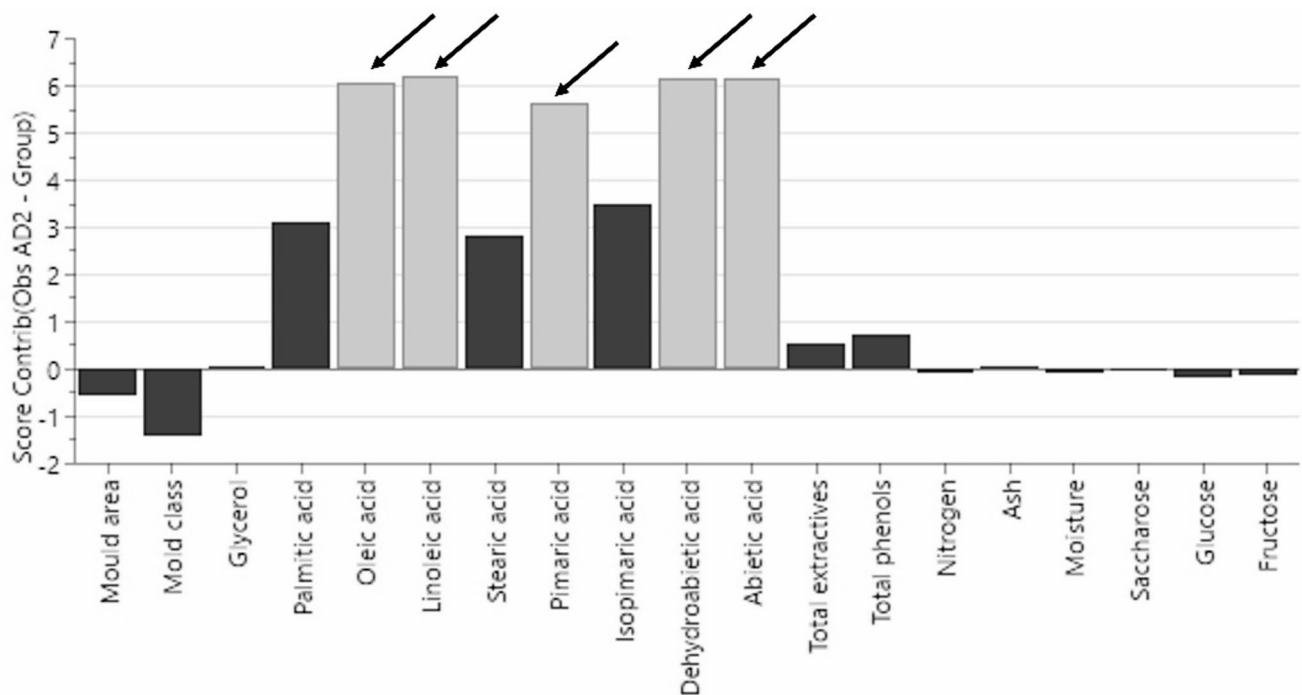


Fig. 3 PCA score contribution plot for AD2 observation. Arrows indicate variables with extreme values. AD2 had extreme values of almost all fatty acids

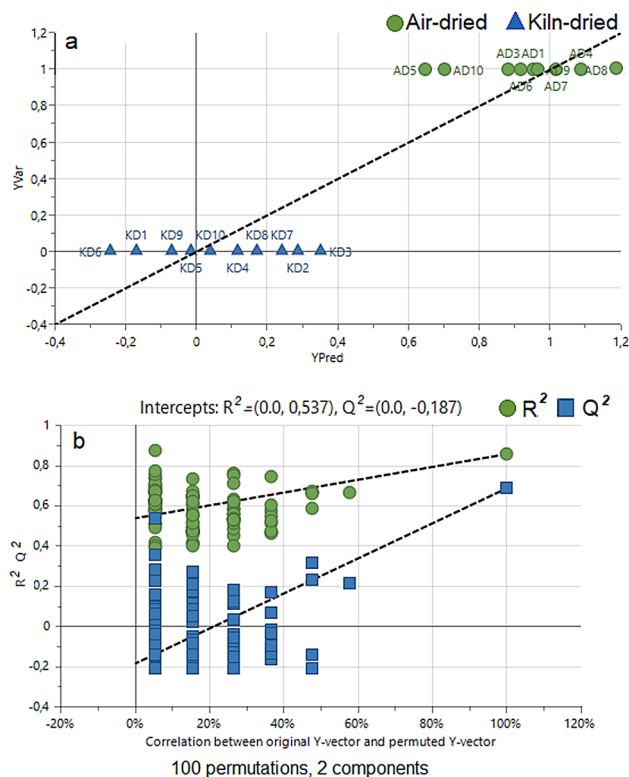


Fig. 4 Observed/predicted plot **a** and validation plot **b** of 100 permutations tests for PLS-DA model created for two drying types of Scots pine sideboards. Observed (YVar) and predicted values (YPred) **a** of the PLS-DA model showing complete separation between the two drying groups. The vertical axis on validation plot **b** gives the R² and Q² values from the permuted analysis. The horizontal axis represents the correlation coefficient between the “real” Y value and the permuted Y value

right and high up in the plot. The air-dried samples show the opposite pattern, with lower values on most variables. Oleic acid is the only chemical compound that seems to be more significant for the air-dried group. A discriminant analysis of the two drying types was executed to simplify the interpretation of the results.

3.3 Partial least-squares discriminant analysis

PLS-DA is a classification approach which allows the prediction of dependent output Y variables (here, sideboard drying types) from input X variables (Eriksson et al. 2006). Qualitatively dividing groups among themselves and visualising the profile of each group by adding group labels as Y variables, the PLS-DA tries to find the model that maximises separation between chosen drying types based on the X-data. Here, PLS-DA was used to determine the characteristics of air- and kiln-dried Scots pine sideboards in relation to surface extractives after 30 days of mould growth. PLS-DA classified air- and kiln-drying types (Y variables)

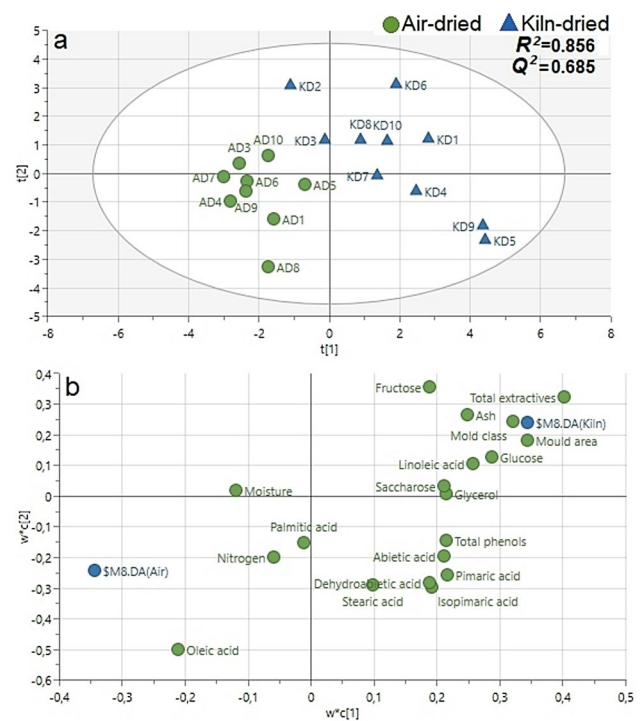


Fig. 5 PLS-DA score plot **(a)** and loading plot **(b)** of component 1 and component 2 for two types of Scots pine board drying. The loading plot is complementary to the score plot and summarises how the extractive and mould class/area variables relate to each other as well as to group variables belonging (\$M8.DA(Air)\$ and \$M8.DA(Kiln)\$ variables showed as blue dots) in the discriminant analysis. The extractive and mould class/area variables located near a group dot are positively associated with that group

based on all extractive variables together with mould class and mould area as X variables.

Two components were significant, and the PLS-DA model explained 85.6% of variations in class ($R^2=0.856$) and a predictive ability of 68.5% ($Q^2=0.685$). The observed/predicted plot in Fig. 4a shows the correctness of the observation discrimination. All observations from the air- and kiln-dried groups were clearly separated. No observation was misclassified. The data set was small and no external test set could be used. Additionally, this model was validated by a permutation test ($n=100$) (Fig. 4b). The R² (green rounds) and Q² (blue squares) values from the permuted analysis (left-bottom corner) are lower than the associated initial values (right-top corner). Intercepts of R² and Q² were 0.537 and -0.187, respectively. The results obtained indicate that this PLS-DA model is significant and valid for interpretation.

In the score plot (Fig. 5a), a clear division of observations into two groups (air- and kiln-dried sideboards) was visualised. The two class variables can be seen in the loading plot marked \$M8.DA(Air) and \$M8.DA(Kiln) (Fig. 5b). They visualise the variance weight for each investigated wood drying type and separated them using the available variables

data. The class variables are located on opposite sides of the plot. In particular, the air-dried type positively correlated with moisture, nitrogen, palmitic and oleic acids. All other 15 variables correlate positively with the kiln-drying type. In general, these results confirm the results obtained from the PCA model.

The two coefficient plots for air- and kiln-drying types are shown as a visual representation of the contribution of each predictor variable to the PLS-DA classification model (Fig. 6a and b). The coefficients are mirrored and describe the difference between the two groups. During the analysis of the coefficient plots, a limitation arose that distorts the results - too large confidence intervals for most of the variables. The standard error will be more minor than the sample size of representative samples increases. However, given the small size of the analysed observations, wide confidence intervals were expected.

A typical predicted Scots pine board dried according to the air-drying method contained more oleic acid and, to some extent, more nitrogen-containing compounds than a kiln-dried. This is also confirmed by the statistical data presented in Table 1. The range of values for oleic acid for air-drying (1.254339 ± 0.403495) is significantly higher than for the kiln-drying method (0.200793 ± 0.339039). The range of nitrogen values is also higher for the air-drying method (0.400752 ± 0.514712) compared to the kiln-drying (0.267047 ± 0.175163). In our data, the air-dried samples had slightly higher moisture on the surface than the kiln-dried samples. The mould growth on air-dried boards is less intense (5–60% of the covered surface), and the mould class is lower. A typical predicted Scots pine board dried according to the kiln-dried method is richer in total extractive and nonorganic components (ash) and contains a higher amount of phenols, low molecular weight sugars, glycerol, some fatty (stearic, linoleic) and resin (pimaric, isopimaric, abietic and dehydroabietic). This is confirmed by the statistics presented in Table 1, where the range of values of these extractives are higher for kiln-drying method compared to air-drying. After our mould test, such a kiln-dried board will likely be covered entirely (90–100% of the covered surface) in high-mould class. It is worth noting that the contribution of palmitic acid is close to zero, which indicates the same amount of this acid on the surface of the sideboards for both types of drying.

The VIP plot shows the specified variables that have the most significant impact on the separation between groups in the PLS-DA model (Fig. 6c). The most influential variables in the PLS-DA model have VIP values of more than 1.0. A total of 6 variables had $VIP > 1$. The total extractives variable was the most influential in the PLS-DA model. Table 4 contains summarised data on all three models presented in the study.

The results show that the total content of extractives, which contains triglycerides and other lipophilic compounds in their composition, was higher on the surface of the sideboards dried in the kiln. Also, the highest content of phenolic components was found on the surface of kiln-dried sideboards. Considering that these components are insoluble (i.e. triglycerides) or appreciably (i.e. phenols) soluble in water, the evaporation and movement of capillary water during the drying process should not affect the distribution of these extractives and their concentration in the surface layers of the Scots pine sideboards. Presumably, the migration of lipophilic components to the wood surface occurs due to the development of a pressure gradient basically in the thickness direction of the board during drying in a kiln chamber (Myronycheva et al. 2018), but this statement requires additional experimental confirmation in future investigations.

More intensive mould growth was observed on the kiln-dried sideboards. At the same time, a significant inhibition of the mould growth of the air-dried sideboards was found. These results are confirmed by data obtained by Sehlstedt-Persson et al. (2011). Possibly, the presence of a greater amount of oleic acid, which has been found to have antifungal properties (Pohl et al. 2011; Guimaraes and Venancio 2022), on the air-dried wood surface contributed to this protective effect. However, this issue requires further detailed investigation.

The extractives from kiln-dried sideboards had high concentrations of low-molecular-weight sugars (glucose, saccharose, fructose). This can be explained by the rapid movement of water with soluble carbohydrates to the wood surface during the kiln-drying process. Heating causes rapid movement and evaporation of water from the capillaries of the wood (Karlsson et al. 2012). At the same time, substances dissolved in water precipitate on the cell walls as water is evaporated and deposited at the wood surface due to liquid or capillary water flow during drying (Theander et al. 1993). That is why extractives from kiln-dried sideboards contained higher amounts of low molecular weight sugars on wood surfaces. In addition, the sugars present in the wood after drying are used as an energy source for more intensive mould growth (Terziev et al. 1997).

Also, a more significant amount of glycerol was detected on the surface of the kiln-dried sideboards, indicating a more intense degradation process of triglycerides during wood drying in the kiln chamber (Myronycheva et al. 2018). In addition, it was found that the ash content on the kiln-dried board surfaces was significantly higher than on the air-dried. The composition of ash includes inorganic components of wood. The concentration of inorganic compounds on the surface of kiln-dried sideboards is likely due to the movement of water-soluble inorganic compounds,

Fig. 6 PLS-DA coefficient plots for air- (a) and kiln-drying (b) types of Scots pine sideboards and the variable importance in projection (VIP) plot (c) for component 1. In the coefficient plots, values of PLS regression coefficients (CoeffCS[1](Air) and CoeffCS[1](Kiln)) for the extractive components and mould growth characteristics are shown. Positive values of CoeffCS indicate that the group has higher values for extractive components or a higher mould class/area than the other group. Conversely, the negative CoeffCS values indicate lower values for variables in this group than in the other group. In the VIP plot, a variable of importance in projection (VIP[1]) scores of each selected variable is shown

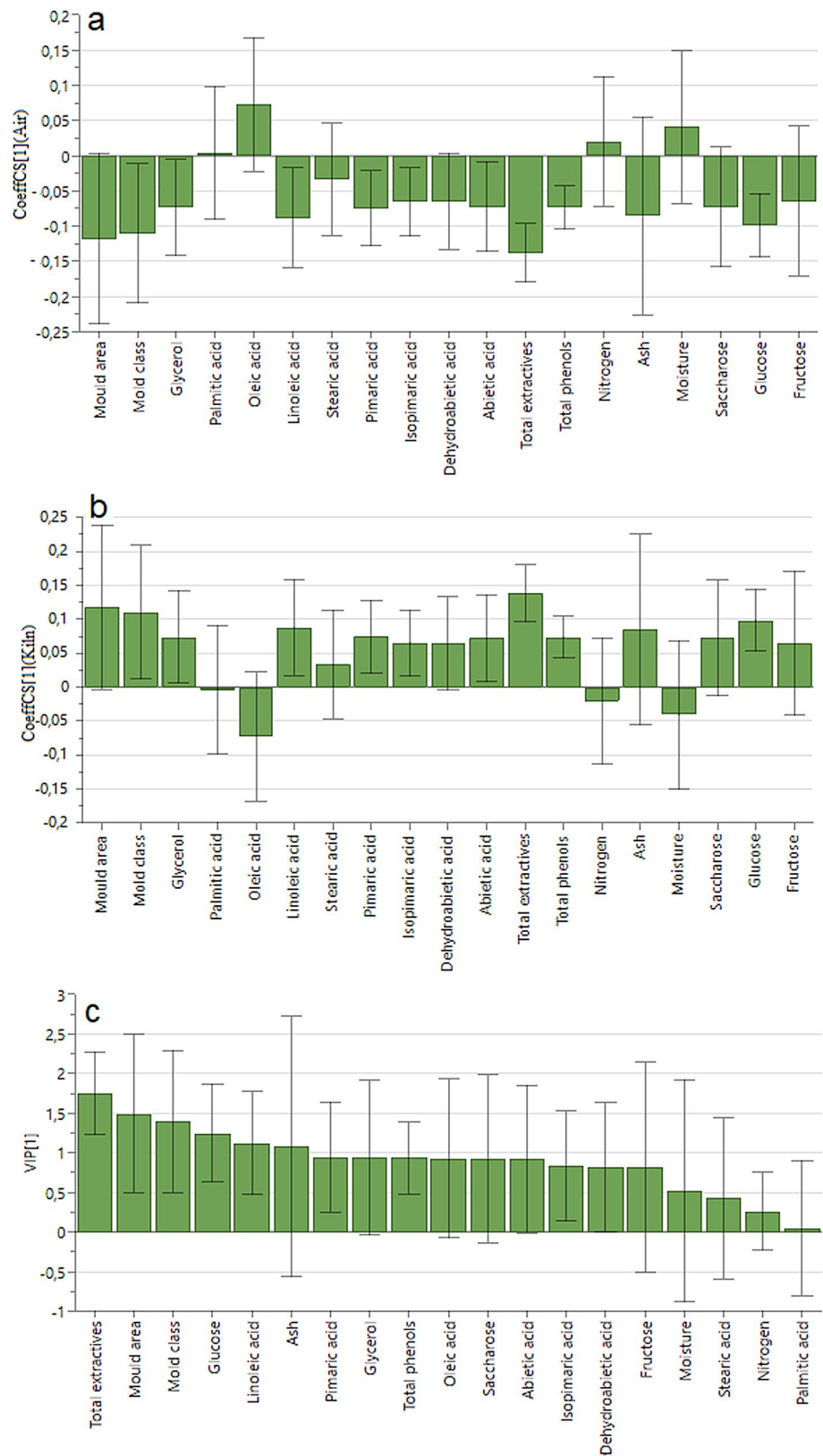


Table 4 The summarised data from PCA and PLS-DA models on drying type of Scots pine sideboards in correlation with mould growth characteristics and extractive composition from the wood surface

Type of model	No. of observations	No. of variables	No. of components	R^2
PCA	20	20	2	0.577
PCA	19 ^a	20	2	0.526
PLS-DA	19 ^a	20	2	0.856

^a AD2 observation was excluded as an outlier

such as potassium-based salts, along with capillary water during drying. A larger amount of nitrogen was detected on the surface of the air-dried sideboards, but this difference was not significant. The reasons for those minor differences are also a more complex question that should not be speculated based on the limited number of samples tested.

The obtained results show that the method of drying Scots pine wood significantly affects the composition and distribution of extractives on the material surface and, accordingly, affects the characteristics of mould growth. Sideboards were more protected from mould growth after air-drying treatment. The kiln-drying method is often used due to the significantly shorter drying time of wood, but it decreases the resistance of Scots pine wood to fungal agents. The Scots pine wood during/or after the kiln-drying process should be additionally treated with anti-fungal agents to prevent rapid mould spread.

4 Conclusion

Multivariate data analysis was used to identify the differences in mould growth features and surface extractive composition of the Scots pine sideboards between the two wood drying methods (air- and kiln-drying). This study presented two PCA and one PLS-DA models, which show clustering of observations by type of wood drying to be identified. Significant differences in the composition of surface extractives and mould growth characteristics between air- and kiln-dried sideboards were found. More intense mould growth was detected on kiln-dried Scots pine sideboards than on air-dried. Higher amounts of oleic acid were found on air-dried surfaces of the sideboards, which may possibly be related to their resistance to mould growth. The kiln-drying method significantly affected the redistribution of wood extractives and contributed to the concentration of lipophilic compounds (total extractives) and phenols on the surface of the boards, presumably due to the development of a pressure gradient basically in the thickness direction of the sideboard during the drying process. At the same time, water-soluble inorganic components and low-molecular-weight sugars, namely glucose, saccharose and fructose, had higher values on the surface of the kiln-dried sideboards caused by

the intense movement of capillary water together with dissolved components to the wood surface. Higher amounts of low-molecular-weight sugars contributed to more intensive mould growth on the kiln-dried wood surface and proved the need for additional antifungal treatment of the wood after/during kiln-drying.

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Author contributions AP: investigation; visualisation; writing – original draft; writing – review & editing. OM: investigation; formal analysis; writing – review & editing. OB: formal analysis; writing – review & editing. OK: conceptualization; project administration; methodology; writing – review & editing.

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Data availability The dataset obtained and analysed in this study is stored on the Luleå University of Technology servers. Access to the data is available by requesting it from the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval and consent to participate Not applicable.

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