Scientific Skills Courses 2024WS Final Report

Effects of Resin Content and Melamine Primer Coating on the Mechanical Strength and Water Resistance Properties of UF/PMDI-Bonded Hardwood& Softwood Particleboard

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Abstract—Particleboard, as an important engineered wood product, is widely used in the construction industry. However, the continuous rise in softwood prices in recent years has led to challenges such as increased raw material costs and supply instability for the particleboard industry. This has prompted the industry to actively explore alternative wood species, particularly the potential of hardwoods in particleboard production. This study employed analysis of variance (ANOVA) and multiple linear regression (MLR) statistical methods to analyze the effects of wood species (hardwoods: oak, beech, and poplar; softwoods: spruce and pine), resin type (urea-formaldehyde UF and polymeric methylene diphenyl diisocyanate PMDI), resin content (UF: 5.5% and 12%; PMDI: 2% and 4%), and melamine primer treatment on the mechanical properties and water resistance of particleboard. The results showed that particleboards bonded with 4% PMDI resin exhibited the best overall performance in terms of mechanical properties and water resistance, with significantly higher internal bond strength and modulus of rupture, as well as the lowest water absorption and thickness swelling rates. In contrast, particleboards bonded with 12% UF resin, while demonstrating high internal bond strength and modulus of rupture, showed poor water resistance, with higher water absorption and thickness swelling rates. Melamine primer treatment significantly improved the long-term water resistance of UF-bonded particleboards, but its effect on PMDI-bonded particleboards was limited. Additionally, hardwood particleboards outperformed softwood particleboards in short-term water resistance, particularly when bonded with PMDI resin, although this advantage diminished under prolonged water exposure. This study quantified the effects of wood species, resin type and content, and surface treatment on particleboard performance. The results indicated that resin type and content had the most significant impact on mechanical properties and water resistance, while the effectiveness of melamine primer treatment varied depending on the resin type and wood species. These findings provide data-driven support for the application of hardwoods in particleboard production and offer valuable references for optimizing resin systems and surface treatment processes.

Keywords—*Particle board, hardwood, softwood, PMDI, UF, melamine primer, water resistance, mechanical property,ANOVA,MLR*

Contents

1. Introduction

Particleboard, as an essential engineered wood product, is widely used in the construction industry. The continuous rise in softwood prices has posed significant challenges to the particleboard industry, including increased raw material costs and supply instability. This has driven the industry to actively explore alternative wood species, particularly the potential application of hardwoods in particleboard production.

This study analyzes the performance differences between particleboards made from hardwoods (oak, beech, and poplar) and traditional softwoods (spruce and pine). By varying content levels (UF: 5.5% and 12%; PMDI: 2% and 4%), the study compares the effects of two typical bonding resins, urea-formaldehyde (UF) and polymeric methylene diphenyl diisocyanate (PMDI), on board mechanical and water resistant properties. Additionally, this research examines the improvement in water resistance of particleboards treated with melamine-based resin coating, as evaluated through measurements of water absorption and thickness swelling parameters.

Through variance analysis and multiple linear regression statistical methods, this study systematically analyzes the influence of wood type, resin type and content, and coasting treatment processes on the mechanical and water-resistant properties of particleboard. The research findings will enhance understanding of hardwood suitability in particleboard manufacturing, reveal the interactions between different adhesive systems and wood species, and provide theoretical basis reference for expanding particleboard raw material sources and optimizing manufacturing processes.

2. Wood type and species for particleboard production

Wood has become the primary raw material for particleboard production due to its unique physical and chemical properties, including renewability, high strength-to-weight ratio, excellent thermal and acoustic insulation, and ease of processing [1]. When selecting wood materials for particleboard manufacturing, several key factors must be comprehensively considered: first, the wood should have stable and sufficient supply sources with reasonable costs to ensure economic viability; second, the raw material should possess moderate density, strength, and dimensional stability, as well as appropriate lignin and cellulose content, as these characteristics directly affect the physical properties and bonding quality of the finished board; furthermore, the wood should demonstrate good machinability, drying properties, and pressing characteristics to ensure efficient production processes [2].

2.1. Hardwood and softwood

Wood materials used in particleboard production are primarily categorized into hardwoods and softwoods.

Hardwoods derived from broad-leaved trees, are typically represented by oak (Quercus spp.) and beech (Fagus sylvatica), characterized by their higher density (500-870 kg/m^3) and shorter fiber length (0.7-1.5 mm), with thick cell walls resulting in higher hardness and strength. Softwoods, originating from conifers such as spruce (Picea abies) and pine (Pinus spp.), have relatively lower density (350-550 kg/m^3), but their longer fibers contribute to good mechanical strength and dimensional stability in particleboard.

Due to their lower cost and and easy to process, softwoods have traditionally dominated particleboard production. However, recent increases in softwood prices and supply constraints have led the industry to explore the potential of hardwoods as alternative raw materials.

2.2. Five wood species for the study

To investigate the suitability of different wood species in particleboard production, Prof. R Wimmer provided data included five representative wood species: oak, beech, poplar, spruce, and pine. The selection of these wood species covers a complete density gradient from high-density hardwoods to low-density softwoods: oak and beech represent high-density hardwoods with densities greater than 700 kg/m^3, poplar serves as a medium-density hardwood with density ranging from 400-600 kg/m^3, while spruce and pine are typical softwoods with densities below 550 kg/m^3. Through statistical analysis of these five wood species' performance in particleboard, the study not only enables statistical evaluation of the feasibility of substituting hardwoods for softwoods but also allows for in-depth study of each wood type's potential advantages in different applications, thereby providing more diverse raw material options for particleboard production.

2.3. Wood particle size and uniformity

The quality of particleboard is largely dependent on the size and uniformity of wood particles, with particle uniformity playing a crucial role in improving board density uniformity, reducing internal stress, and enhancing surface quality [3]. When particles are oversized or unevenly distributed, the board may exhibit density variations, consequently affecting its mechanical properties and surface smoothness. To ensure research reliability and accuracy in comparing different wood species, this study assumes that all samples employ controllable particle size and uniformity parameters, with wood chips of uniform dimensions being used in particleboard manufacturing.

3. Methodology

This study employed statistical analyses to evaluate the effects of wood species, resin type and content, and primer coating on particleboard mechanical and water resistant properties. Two primary resin systems were investigated: polymeric methylene

diphenyl diisocyanate (PMDI) and urea-formaldehyde (UF) resin, applied at two distinct levels - PMDI at 2% and 4%, and UF at 5.5% and 12%.
For particleboards without Melamine Primer Coating, two-way ANOVA was conducted separately for UF-bonded and PMDI-bonded groups to assess the effeects of wood type and resin content on mechanical properties and water resistance. The analysis followed the procedure: data processing, Shapiro-Wilk normality test, Levene's test for homogeneity of variance, followed by either Welch-ANOVA (for non-homogeneous variance) or traditional two-way ANOVA (for homogeneous variance), and post-hoc analysis using either Games-Howell test or Tukey HSD, descriptive statistics.
The data from both groups were then combined for three-way ANOVA to evaluate the effects of wood type, resin type, and content on particleboard mechanical and water resistant properties. This analysis included data processing, descriptive statistics, Shapiro-Wilk test, Levene's test, followed by either Type III SS ANOVA (for non-homogeneous variance) or traditional ANOVA (for homogeneous variance), and appropriate post-hoc analysisdescriptive statistics.
To explore potential improvements in water resistance, selected particleboards from both UF and PMDI groups were treated with melamine-based primer (Madurit MW840). Multiple linear regression (MLR) analysis was conducted separately for UF-bonded and PMDI-bonded groups to assess the effects of average density, resin content, and melamine primer on water resistance. The MLR analysis involved data processing with categorical variable conversion to factors, correlation analysis between density and water resistance, and regression analysis.

3.1. Physical performance of particleboard

In the provided dataset, six key performance indicators were measured: modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IB), density (including average, maximum, and minimum density), and both short-term and long-term water absorption (2-hour and 24-hour) with corresponding thickness swelling rates. These indicators can be regard as reflection of particleboard's mechanical strength, structural stability, and water resistance properties. Through statistical analysis of potential influencing factors such as wood type, resin type and content, and pretreatment coating, the data allows inference of their impact levels on particleboard's mechanical and water resistance performance.

3.2. Data source and analysis tools

The experimental dataset and some related research [4],[5],[6],[7],[8],[9],[10] provided by Prof. R Wimmer, consists of 80 wood test samples encompassing five different wood species with 16 samples per species. Each wood type was tested with two resin types and two primer treatments, with four replications for each treatment combination ($2 \times 2 \times 4 = 16$). This balanced experimental design ensures equal sample sizes across wood species while providing sufficient replications for statistical significance. For each sample, 16 key parameters were recorded, including physical properties (such as density, water absorption, and thickness swelling) and mechanical properties (including bending strength, modulus of elasticity, and internal bond strength). All Data analysis was conducted using R programming language, incorporating descriptive statistics, analysis of variance (ANOVA), regression analysis, and correlation analysis to systematically evaluate the effects and interactions of various factors on particleboard performance.

4. Resination for bonding

Resination is a bonding technique designed to enhance particle cohesion within particleboard, primarily aimed at improving mechanical properties (modulus of rupture, modulus of elasticity, internal bond strength) and, to some extent, water resistance. Based on bonding mechanisms, resination can be classified into physical and chemical bonding.
Physical bonding is typically represented by adhesives such as urea-formaldehyde (UF) resin, certain phenol-formaldehyde (PF) resins, and polyvinyl acetate (PVAc); while chemical bonding is characterized by adhesives including polymeric methylene diphenyl diisocyanate (PMDI), melamine-formaldehyde (MF), and modified PF resins capable of crosslinking with wood components [11].
This chapter presents ANOVA of particleboards without coating treatment, comparing the effects of different wood types, resination type (UF resin and PMDI) and contents on mechanical properties and water resistance, thereby providing an in-depth investigation of how these factors influence particleboard mechanical and water resistant performance.

4.1. Physical Bonding UF(5.5/12%)

UF bonding is a physical adhesion method that provides mechanical bonding by filling the gaps between wood particles and forming a network structure after curing. It does not chemically react with wood cell walls and therefore does not alter the inherent chemical structure of wood [11].
This subsection analyzes the effects of UF resin content and wood type on the mechanical properties of particleboard. Prior to ANOVA analysis, data quality was first confirmed through prerequisite tests, with Shapiro-Wilk tests showing normal distribution for all groups ($p > 0.05$), and Levene's tests indicating variance homogeneity for MOE and MOR but not for IB. For internal bond strength (IB), Welch's ANOVA was employed due to variance heterogeneity ($F = 13.035$, $p = 0.001693$), revealing that resin content had a strong effect size ($\eta^2 = 0.717$), with the high resin content group showing significantly higher IB values than the low resin content group ($p < 0.01$), while wood type had minimal impact ($\eta^2 = 0.155$) and interaction effects were small ($\eta^2 = 0.070$).
Modulus of elasticity (MOE) analysis showed significant main effects of resin content ($p = 0.00587$) with moderate effect size

($\eta^2 = 0.387$), with the high resin content group showing significantly higher MOE values, while wood type and its interaction with resin content were not significant ($p = 0.958$, $p = 0.485$). Modulus of rupture (MOR) analysis similarly found highly significant resin content effects ($p = 0.000481$) with large effect size ($\eta^2 = 0.544$), with the high resin content group consistently showing higher MOR values, while wood type showed only marginally significant effects ($p = 0.082$) and no significant interaction ($p = 0.880$).

Collectively, these results indicate that resin content is the dominant factor affecting all three mechanical properties, with the strongest impact on IB ($\eta^2 = 0.717$), followed by MOR ($\eta^2 = 0.544$) and MOE ($\eta^2 = 0.387$); higher resin content consistently led to better mechanical properties, while wood type and its interaction with resin content had relatively minor effects. These statistical findings were supported by interaction plots and box plots, which clearly demonstrated the significant differences between high and low resin content groups and the relatively small differences between wood types.

Prior to analyzing the water resistance of UF particleboard, data quality assessment was first conducted. Shapiro-Wilk normality tests indicated that all test groups showed normal distribution except for Quell24h of high-resin hardwood ($p = 0.0309$) and WA24h of low-resin softwood ($p = 0.0405$). Levene's test for homogeneity of variance showed that only WA24h had variance homogeneity, while Quell24h, Quell2h, and WA2h exhibited heterogeneous variances, thus Welch's ANOVA was employed for these three indicators for more robust analysis. The analysis results showed that the overall model for Quell24h was significant ($p = 0.01029$), with resin content effects explaining 62.5% (0.625162218) of the variance, and post-hoc comparisons further confirmed significant differences between high and low resin contents in hardwood ($p = 0.027$). For WA24h with homogeneous variance, traditional two-way ANOVA revealed a highly significant main effect of resin content ($p < 0.001$), explaining 77.2% (0.771586417) of the variance, while wood type effects ($p = 0.242$) and interaction effects ($p = 0.797$) were not significant. WA2h also showed a highly significant overall effect ($p = 0.0009174$), with resin content effects explaining 79.2% (0.791747647) of the variance, and post-hoc comparisons indicated significant differences between high and low resin contents in the hardwood group ($p = 0.003$). In contrast, Quell2h showed no significant differences ($p = 0.2604$), with its largest effect (wood type) being only 9.2%(0.091523464). Interaction plot analysis revealed that low resin content groups generally showed higher values in WA24h and Quell24h tests, with both indicators showing similar trends; WA2h displayed obvious main effects of resin content with similar response patterns between softwood and hardwood; while Quell2h showed weak interaction effects with nearly parallel trend lines. The research results indicate that resin content is the dominant factor affecting the water resistance of UF particleboard, particularly significant in WA24h and WA2h indicators, while wood type had relatively minor effects.

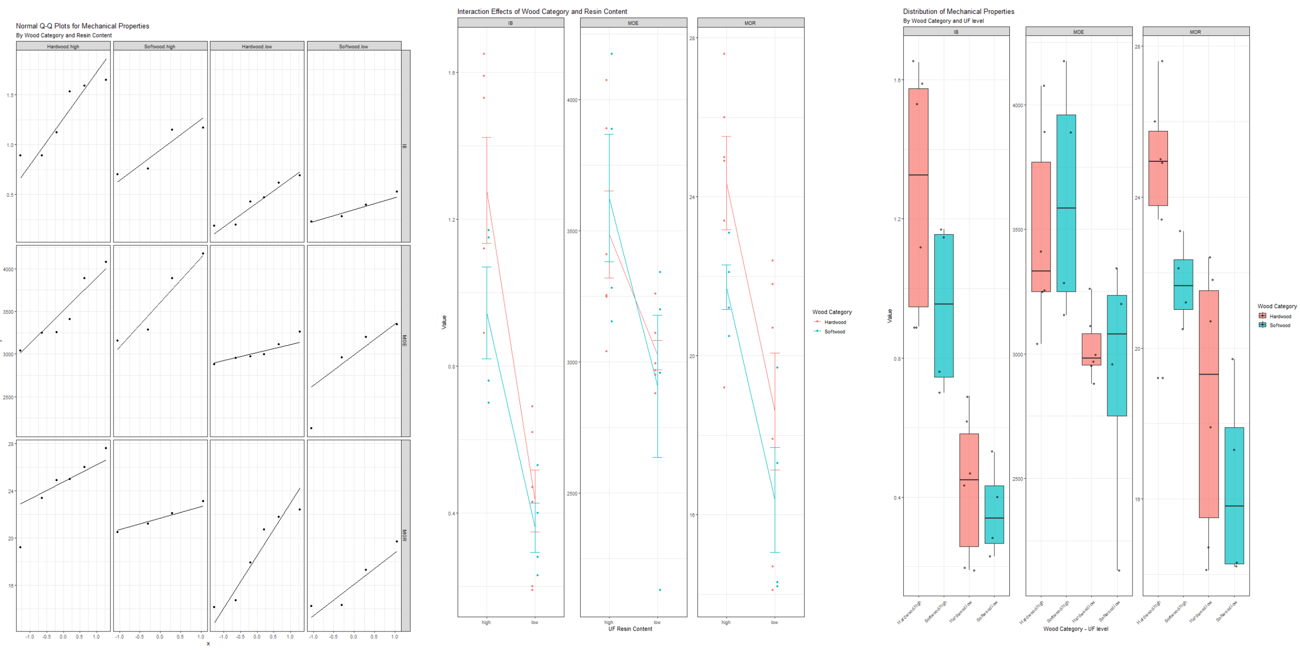
4.2. UF(5.5/12%) Particleboard Two-way ANOVA results

```
# Woodtype&UFlevel influence on the M-Strength
*******************************************
1. Normality Test Results (Shapiro-Wilk):
*******************************************
# A tibble: 12 x 7
   LeimgradCode WoodCategory Property variable statistic     p Normality
   <chr>        <chr>        <chr>    <chr>        <dbl> <dbl> <chr>
 1 high         Hardwood     IB       Value        0.832 0.112 Normal
 2 low          Hardwood     IB       Value        0.909 0.432 Normal
 3 high         Softwood     IB       Value        0.805 0.111 Normal
 4 low          Softwood     IB       Value        0.951 0.720 Normal
 5 high         Hardwood     MOE      Value        0.895 0.347 Normal
 6 low          Hardwood     MOE      Value        0.912 0.452 Normal
 7 high         Softwood     MOE      Value        0.906 0.460 Normal
 8 low          Softwood     MOE      Value        0.866 0.281 Normal
 9 high         Hardwood     MOR      Value        0.910 0.435 Normal
10 low          Hardwood     MOR      Value        0.883 0.282 Normal
11 high         Softwood     MOR      Value        0.985 0.931 Normal
12 low          Softwood     MOR      Value        0.874 0.314 Normal
*************************************************************************************
2. Homogeneity of Variance Test Results (Levene's Test):
*************************************************************************************
# A tibble: 3 x 3
  Property levene_test     Homogeneity
  <chr>    <list>          <chr>
1 IB       <anova [2 x 3]> Non-homogeneous
2 MOE      <anova [2 x 3]> Homogeneous
3 MOR      <anova [2 x 3]> Homogeneous
*******************************************
3. Analysis Results:
*******************************************
Results for IB :

        One-way analysis of means (not assuming equal variances)

data:  Value and interaction(WoodCategory, LeimgradCode)
F = 13.035, num df = 3.000, denom df = 8.275, p-value = 0.001693


Results for MOE :
                          Df  Sum Sq Mean Sq F value  Pr(>F)
WoodCategory               1     456     456   0.003 0.95766
LeimgradCode               1 1582031 1582031  10.085 0.00587 **
WoodCategory:LeimgradCode  1   80083   80083   0.511 0.48521
Residuals                 16 2509860  156866
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Results for MOR :
                          Df Sum Sq Mean Sq F value   Pr(>F)
WoodCategory               1  28.23   28.23   3.442 0.082097 .
LeimgradCode               1 156.24  156.24  19.049 0.000481 ***
WoodCategory:LeimgradCode  1   0.19    0.19   0.023 0.880310
Residuals                 16 131.23    8.20
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
*******************************************
4. Effect Sizes Results:
*******************************************
  Property                 Parameter  Eta_squared    CI_low CI_high
1      MOR              WoodCategory 0.1770195100 0.0000000       1
2      MOR              LeimgradCode 0.5435009853 0.2388227       1
3      MOR WoodCategory:LeimgradCode 0.0014609426 0.0000000       1
4      MOE              WoodCategory 0.0001817699 0.0000000       1
5      MOE              LeimgradCode 0.3866259591 0.0889897       1
6      MOE WoodCategory:LeimgradCode 0.0309208864 0.0000000       1
7       IB              WoodCategory 0.1550210779 0.0000000       1
8       IB              LeimgradCode 0.7173550357 0.4796105       1
9       IB WoodCategory:LeimgradCode 0.0697604421 0.0000000       1
*******************************************
5. Post-hoc Analysis Results:
*******************************************
Post-hoc Results for IB :
# A tibble: 6 x 8
  .y.   group1        group2        estimate conf.low conf.high p.adj p.adj.signif
* <chr> <chr>         <chr>            <dbl>    <dbl>     <dbl> <dbl> <chr>
1 Value Hardwood.high Softwood.high  -0.333    -0.946    0.279  0.363 ns
2 Value Hardwood.high Hardwood.low   -0.845    -1.38    -0.310  0.004 **
3 Value Hardwood.high Softwood.low   -0.918    -1.45    -0.389  0.003 **
4 Value Softwood.high Hardwood.low   -0.512    -1.04     0.0200 0.058 ns
5 Value Softwood.high Softwood.low   -0.585    -1.13    -0.0442 0.038 *
6 Value Hardwood.low  Softwood.low   -0.0733   -0.419    0.273  0.902 ns

Post-hoc Results for MOE :
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Value ~ WoodCategory * LeimgradCode, data = data_subset)

$WoodCategory
                  diff       lwr      upr     p adj
Softwood-Hardwood 9.75  -373.4809 392.9809 0.9576557

$LeimgradCode
           diff       lwr       upr     p adj
low-high  -562.5  -937.9881 -187.0119 0.0058695

$`WoodCategory:LeimgradCode`
                                diff        lwr       upr     p adj
Softwood:high-Hardwood:high  138.9167  -592.5255 870.35880 0.9469974
Hardwood:low-Hardwood:high  -459.1667 -1113.3884 195.05507 0.2259888
Softwood:low-Hardwood:high  -578.5833 -1310.0255 152.85880 0.1486915
Hardwood:low-Softwood:high  -598.0833 -1329.5255 133.35880 0.1303744
Softwood:low-Softwood:high  -717.5000 -1518.7547  83.75471 0.0876066
Softwood:low-Hardwood:low   -119.4167  -850.8588 612.02547 0.9652010


Post-hoc Results for MOR :
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Value ~ WoodCategory * LeimgradCode, data = data_subset)

$WoodCategory
                    diff       lwr       upr     p adj
Softwood-Hardwood -2.425  -5.196101 0.3461013 0.0820967

$LeimgradCode
          diff       lwr       upr     p adj
low-high  -5.59  -8.305114 -2.874886 0.0004814

$`WoodCategory:LeimgradCode`
                              diff         lwr        upr     p adj
Softwood:high-Hardwood:high -2.625   -7.913979  2.6639787 0.5056334
Hardwood:low-Hardwood:high  -5.750  -10.480606 -1.0193936 0.0147979
Softwood:low-Hardwood:high  -7.975  -13.263979 -2.6860213 0.0027047
Hardwood:low-Softwood:high  -3.125   -8.413979  2.1639787 0.3603482
Softwood:low-Softwood:high  -5.350  -11.143786  0.4437859 0.0756151
Softwood:low-Hardwood:low   -2.225   -7.513979  3.0639787 0.6334467
```

Code 1. Anova results of Wood type and UF-content on mechanical property

```
# Woodtype & UF-level influence on the Water resistant property
*******************************************
1. Normality Test Results (Shapiro-Wilk):
```



(a) Normal QQ-plot

(b) Interaction effects of wood type and resine content

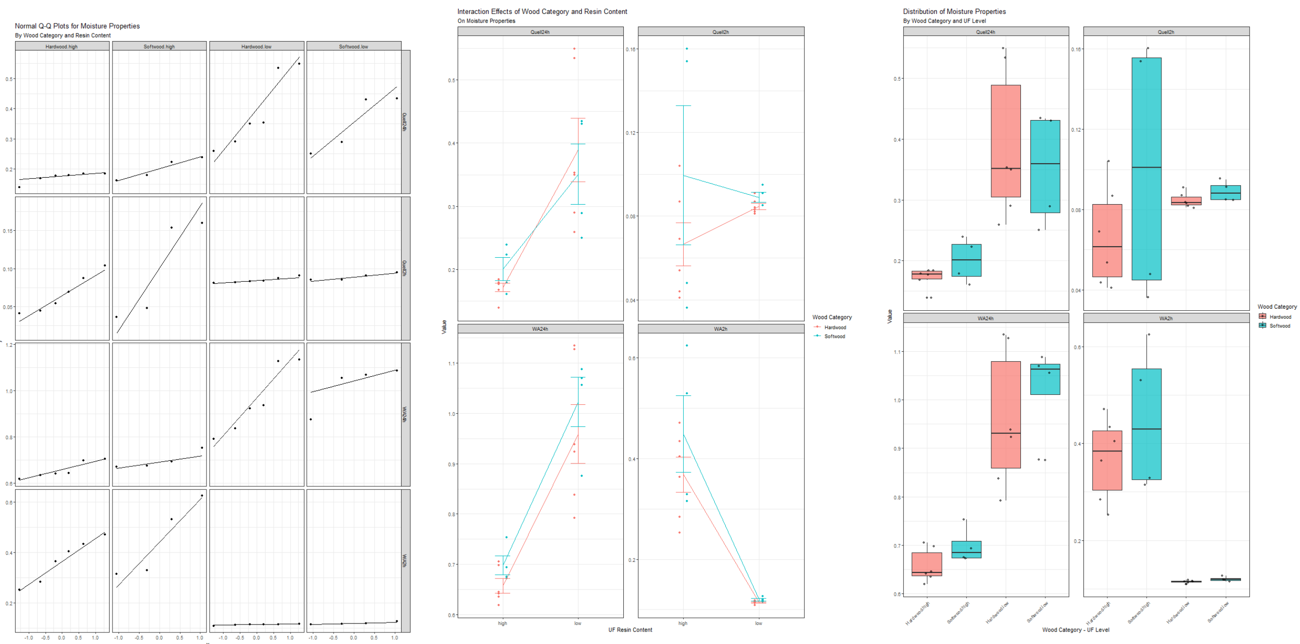
(c) Distribution of the mechanical property

Figure 1. Analysis of effects of Wood type and UF-content on mechanical property

```
********************************************
# A tibble: 16 x 7
   LeimgradCode WoodCategory Property variable statistic      p Normality
   <chr>        <chr>        <chr>    <chr>        <dbl>  <dbl> <chr>
 1 high         Hardwood     Quell24h Value        0.770 0.0309 Non-normal
 2 low          Hardwood     Quell24h Value        0.855 0.174  Normal
 3 high         Softwood     Quell24h Value        0.925 0.568  Normal
 4 low          Softwood     Quell24h Value        0.827 0.160  Normal
 5 high         Hardwood     Quell2h  Value        0.924 0.532  Normal
 6 low          Hardwood     Quell2h  Value        0.905 0.405  Normal
 7 high         Softwood     Quell2h  Value        0.794 0.0927 Normal
 8 low          Softwood     Quell2h  Value        0.860 0.262  Normal
 9 high         Hardwood     WA24h    Value        0.854 0.170  Normal
10 low          Hardwood     WA24h    Value        0.887 0.301  Normal
11 high         Softwood     WA24h    Value        0.815 0.133  Normal
12 low          Softwood     WA24h    Value        0.752 0.0405 Non-normal
13 high         Hardwood     WA2h     Value        0.944 0.695  Normal
14 low          Hardwood     WA2h     Value        0.928 0.567  Normal
15 high         Softwood     WA2h     Value        0.869 0.293  Normal
16 low          Softwood     WA2h     Value        0.944 0.677  Normal
****************************************************************************
2. Homogeneity of Variance Test Results (Levene's Test):
****************************************************************************
# A tibble: 4 x 3
  Property levene_test     Homogeneity
  <chr>    <list>          <chr>
1 Quell24h <anova [2 x 3]> Non-homogeneous
2 Quell2h  <anova [2 x 3]> Non-homogeneous
3 WA24h    <anova [2 x 3]> Homogeneous
4 WA2h     <anova [2 x 3]> Non-homogeneous
********************************************
3. Analysis Results:
********************************************
Results for Quell24h :

        One-way analysis of means (not assuming equal variances)

data:  Value and interaction(WoodCategory, LeimgradCode)
F = 9.0094, num df = 3.0000, denom df = 6.4425, p-value = 0.01029


Results for Quell2h :

        One-way analysis of means (not assuming equal variances)

data:  Value and interaction(WoodCategory, LeimgradCode)
F = 1.6662, num df = 3.0000, denom df = 6.9538, p-value = 0.2604


Results for WA24h :
                          Df Sum Sq Mean Sq F value   Pr(>F)
WoodCategory               1 0.0132  0.0132   1.479    0.242
```

```
LeimgradCode               1 0.4821  0.4821  54.048 1.63e-06 ***
WoodCategory:LeimgradCode  1 0.0006  0.0006   0.068    0.797
Residuals                 16 0.1427  0.0089
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Results for WA2h :

        One-way analysis of means (not assuming equal variances)

data:  Value and interaction(WoodCategory, LeimgradCode)
F = 20.977, num df = 3.0000, denom df = 6.6098, p-value = 0.0009174
*******************************************
4. Effect Sizes Results:
*******************************************
   Property                  Parameter Eta_squared    CI_low CI_high
1    Quell2h              WoodCategory 0.091523464 0.0000000       1
2    Quell2h              LeimgradCode 0.013339250 0.0000000       1
3    Quell2h WoodCategory:LeimgradCode 0.056068638 0.0000000       1
4   Quell24h              WoodCategory 0.001047429 0.0000000       1
5   Quell24h              LeimgradCode 0.625162218 0.3426553       1
6   Quell24h WoodCategory:LeimgradCode 0.047289100 0.0000000       1
7       WA2h              WoodCategory 0.078493102 0.0000000       1
8       WA2h              LeimgradCode 0.791747647 0.6039072       1
9       WA2h WoodCategory:LeimgradCode 0.060499381 0.0000000       1
10     WA24h              WoodCategory 0.084598219 0.0000000       1
11     WA24h              LeimgradCode 0.771586417 0.5691044       1
12     WA24h WoodCategory:LeimgradCode 0.004239072 0.0000000       1
*******************************************
5. Post-hoc Analysis Results:
*******************************************
Post-hoc Results for Quell24h :
# A tibble: 6 x 8
  .y.   group1        group2        estimate conf.low conf.high p.adj p.adj.signif
* <chr> <chr>         <chr>            <dbl>    <dbl>     <dbl> <dbl> <chr>
1 Value Hardwood_high Hardwood_low    0.217    0.0323    0.402   0.027 *
2 Value Hardwood_high Softwood_high   0.0287  -0.0521    0.109   0.531 ns
3 Value Hardwood_high Softwood_low    0.179   -0.0466    0.404   0.092 ns
4 Value Hardwood_low  Softwood_high  -0.189   -0.372    -0.00523 0.045 *
5 Value Hardwood_low  Softwood_low   -0.0384  -0.262     0.186   0.943 ns
6 Value Softwood_high Softwood_low    0.150   -0.0609    0.361   0.134 ns

Post-hoc Results for Quell2h :
# A tibble: 6 x 8
  .y.   group1        group2        estimate conf.low conf.high p.adj p.adj.signif
* <chr> <chr>         <chr>            <dbl>    <dbl>     <dbl> <dbl> <chr>
1 Value Hardwood_high Hardwood_low   0.0182  -0.0194      0.0557 0.386 ns
2 Value Hardwood_high Softwood_high  0.033   -0.118       0.184  0.785 ns
3 Value Hardwood_high Softwood_low   0.0225  -0.0149      0.0599 0.249 ns
4 Value Hardwood_low  Softwood_high  0.0148  -0.146       0.175  0.966 ns
5 Value Hardwood_low  Softwood_low   0.00433 -0.00608     0.0148 0.496 ns
6 Value Softwood_high Softwood_low  -0.0105  -0.170       0.149  0.987 ns

Post-hoc Results for WA24h :
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Value ~ WoodCategory * LeimgradCode, data = data_subset)

$WoodCategory
                        diff         lwr       upr     p adj
Softwood-Hardwood 0.05241667 -0.03896333 0.1437967 0.2416204

$LeimgradCode
            diff       lwr       upr   p adj
low-high 0.3105 0.2209663 0.4000337 1.6e-06

$`WoodCategory:LeimgradCode`
                                  diff         lwr       upr     p adj
Softwood:high-Hardwood:high 0.04116667 -0.13324299 0.2155763 0.9049141
Hardwood:low-Hardwood:high  0.30150000  0.14550326 0.4574967 0.0002420
Softwood:low-Hardwood:high  0.36516667  0.19075701 0.5395763 0.0001009
Hardwood:low-Softwood:high  0.26033333  0.08592367 0.4347430 0.0029544
Softwood:low-Softwood:high  0.32400000  0.13294379 0.5150562 0.0009153
Softwood:low-Hardwood:low   0.06366667 -0.11074299 0.2380763 0.7266280


Post-hoc Results for WA2h :
# A tibble: 6 x 8
  .y.   group1        group2        estimate conf.low conf.high p.adj p.adj.signif
* <chr> <chr>         <chr>            <dbl>    <dbl>     <dbl> <dbl> <chr>
1 Value Hardwood_high Hardwood_low  -0.254   -0.383      -0.125  0.003 **
2 Value Hardwood_high Softwood_high  0.0812  -0.249       0.411  0.773 ns
3 Value Hardwood_high Softwood_low  -0.248   -0.377      -0.120  0.003 **
4 Value Hardwood_low  Softwood_high  0.335   -0.0321      0.702  0.064 ns
5 Value Hardwood_low  Softwood_low   0.00567 -0.00531     0.0166 0.313 ns
6 Value Softwood_high Softwood_low  -0.330   -0.696       0.0375 0.066 ns
```

Code 2. Anova results of Wood type and UF-content on water resistant ptoperty



(a) Normal QQ-plot

(b) Interaction effects of wood type and resine content

(c) Distribution of the water resistant property

Figure 2. Analysis of effects of Wood type and UF-content on water resistant property

4.3. Chemical Bonding PMDI(2/4%)

PMDI bonding not only forms an adhesive layer but also chemically reacts with wood, creating stronger bonds. As an isocyanate adhesive, PMDI's –N=C=O groups react with wood's hydroxyl groups (–OH) to form polyurethane cross-linking structures, thus considered chemical bonding. Theoretically, PMDI bonding enhances particle bonding strength and reduces water penetration potential [5].

This section analyzes the effects of wood type and PMDI content on particleboard mechanical properties through two-way ANOVA and related statistical tests. Data quality assessment showed normal distribution for all experimental combinations except MOR data in the Hardwood-low group (Shapiro-Wilk test, $p > 0.05$), while Levene's test confirmed variance homogeneity for IB, MOE, and MOR, establishing a statistical foundation for parametric testing. Two-way ANOVA revealed PMDI content's dominant role in board performance: strongest effect on internal bond strength (IB) ($\eta^2 = 0.64$, $p < 0.001$), followed by modulus of rupture (MOR) ($\eta^2 = 0.30$, $p = 0.0197$), with marginal significance for modulus of elasticity (MOE) ($\eta^2 = 0.17$, $p = 0.087$). In contrast, wood type showed no significant main effects on any performance indicators (IB: $F(1, 16) = 1.092$, $p = 0.312$, $\eta^2 = 0.064$; MOE: $F(1, 16) = 0.094$, $p = 0.763$, $\eta^2 = 0.006$; MOR: $F(1, 16) = 1.688$, $p = 0.212$, $\eta^2 = 0.095$), and no significant interaction effects between wood type and PMDI content were observed (IB: $F(1, 16) = 0.381$, $p = 0.546$, $\eta^2 = 0.023$; MOE: $F(1, 16) = 0.334$, $p = 0.571$, $\eta^2 = 0.020$; MOR: $F(1, 16) = 0.127$, $p = 0.727$, $\eta^2 = 0.008$). These findings indicate that hardwood versus softwood selection does not significantly affect board properties, and PMDI content's enhancement effects do not significantly vary by wood type. Interaction plots graphically verified these results, showing nearly parallel trend lines for all performance indicators, confirming no significant interactions. Box plots further demonstrated consistently higher performance values in high-PMDI groups compared to low-PMDI groups, with moderate data dispersion and no significant outliers. Based on statistical analysis, PMDI content emerges as the decisive parameter in controlling particleboard mechanical properties, with its impact significantly outweighing wood type selection effects.

Additionally, the same analytical approach was used to investigate the effects of PMDI content and wood type on particleboard water resistance properties. Initial data quality assessment revealed non-normal distribution and variance heterogeneity characteristics in the experimental data, leading to the adoption of more robust statistical methods. Specifically, for indicators with heterogeneous variance, which are 24-hour thickness swellingQuell24h), 2-hour thickness swelling(Quell2h), and 2-hour water absorption(WA2h) Welch-ANOVA was employed, showing no significant differences between treatment groups (Quell24h:$F = 2.649$, $p = 0.145$; Quell2h: $F = 3.381$, $p = 0.098$; WA2h:$F = 2.607$, $p = 0.149$). For 24-hour water absorption (WA24h), which met statistical assumptions, traditional two-way ANOVA revealed no significant effects from wood type ($F(1, 16) = 1.013$, $p = 0.329$, $\eta^2 = 0.060$), PMDI content ($F(1, 16) = 1.750$, $p = 0.205$, $\eta^2 = 0.099$), or their interaction ($F(1, 16) = 0.057$, $p = 0.814$, $\eta^2 = 0.004$). Although differences did not reach statistical significance, effect size analysis revealed certain trends: wood type showed larger effects on short-term (2-hour) water resistance properties (thickness swelling $\eta^2 = 0.313$, water absorption $\eta^2 = 0.293$), while PMDI content primarily influenced long-term (24-hour) thickness swelling performance ($\eta^2 = 0.189$). These findings were also visually supported by descriptive statistics (box plots), indicating that softwood groups and low PMDI content groups tended to have higher water absorption and thickness swelling rates.

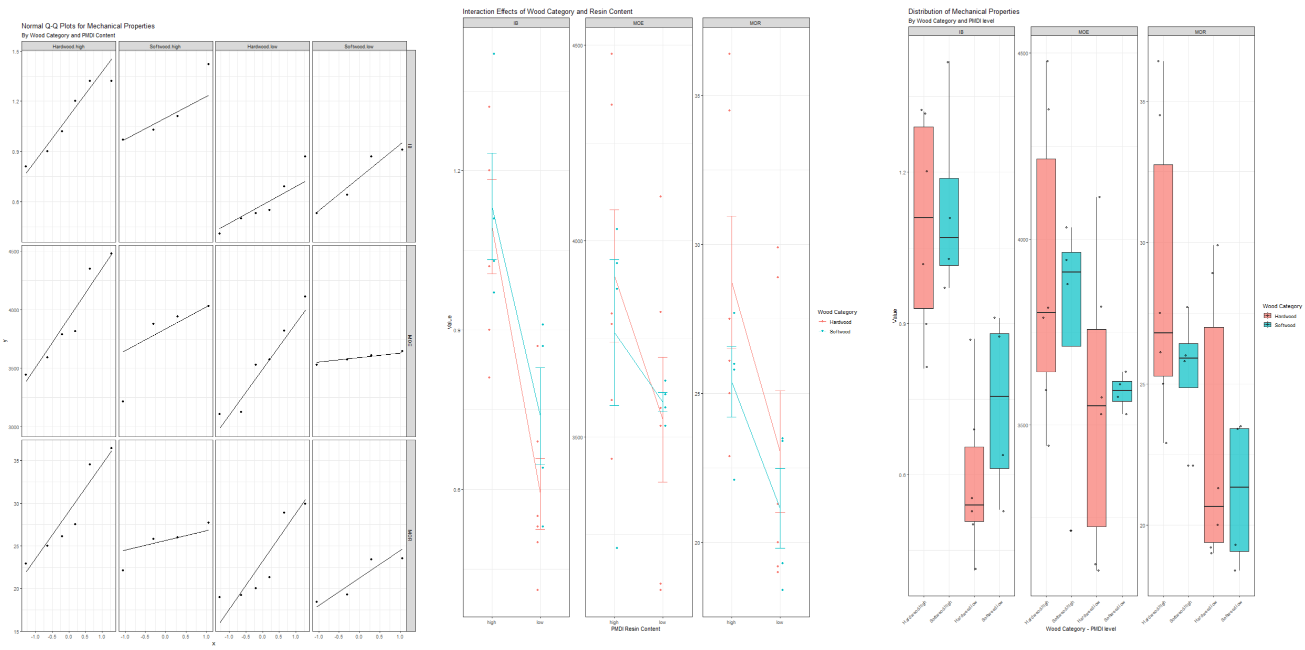
4.4. PMDI(2/4%) Particleboard Two-way ANOVA results

```
------------------------------------------------------
# Woodtype & PMDI-level influence on the M-Strength
******************************************************
1. Normality Test Results (Shapiro-Wilk):
# A tibble: 12 x 7
   LeimgradCode WoodCategory Property variable statistic      p Normality
   <chr>        <chr>        <chr>    <chr>        <dbl>  <dbl> <chr>
 1 high         Hardwood     IB       Value        0.899 0.367  Normal
 2 low          Hardwood     IB       Value        0.918 0.492  Normal
 3 high         Softwood     IB       Value        0.867 0.284  Normal
 4 low          Softwood     IB       Value        0.898 0.419  Normal
 5 high         Hardwood     MOE      Value        0.903 0.393  Normal
 6 low          Hardwood     MOE      Value        0.932 0.595  Normal
 7 high         Softwood     MOE      Value        0.781 0.0728 Normal
 8 low          Softwood     MOE      Value        0.993 0.973  Normal
 9 high         Hardwood     MOR      Value        0.886 0.299  Normal
10 low          Hardwood     MOR      Value        0.777 0.0363 Non-normal
11 high         Softwood     MOR      Value        0.902 0.443  Normal
12 low          Softwood     MOR      Value        0.813 0.127  Normal

2. Homogeneity of Variance Test Results (Levene's Test):
# A tibble: 3 x 3
  Property levene_test     Homogeneity
  <chr>    <list>          <chr>
1 IB       <anova [2 x 3]> Homogeneous
2 MOE      <anova [2 x 3]> Homogeneous
3 MOR      <anova [2 x 3]> Homogeneous

3. Two-way ANOVA Results:

ANOVA Results for IB :
                          Df Sum Sq Mean Sq F value   Pr(>F)
WoodCategory               1 0.0403  0.0403   1.092    0.312
LeimgradCode               1 1.0580  1.0580  28.634 6.49e-05 ***
WoodCategory:LeimgradCode  1 0.0141  0.0141   0.381    0.546
Residuals                 16 0.5912  0.0369
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

ANOVA Results for MOE :
                          Df  Sum Sq Mean Sq F value Pr(>F)
WoodCategory               1   12000   12000   0.094 0.7633
LeimgradCode               1  423987  423987   3.314 0.0874 .
WoodCategory:LeimgradCode  1   42714   42714   0.334 0.5714
Residuals                 16 2046904  127931
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

ANOVA Results for MOR :
                          Df Sum Sq Mean Sq F value Pr(>F)
WoodCategory               1  32.87   32.87   1.688 0.2122
LeimgradCode               1 130.56  130.56   6.707 0.0197 *
WoodCategory:LeimgradCode  1   2.47    2.47   0.127 0.7266
Residuals                 16 311.46   19.47
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

4. Effect Sizes Results:
  Property                 Parameter Eta_squared     CI_low CI_high
1      MOR              WoodCategory 0.095448953 0.00000000       1
2      MOR              LeimgradCode 0.295373161 0.03249893       1
3      MOR WoodCategory:LeimgradCode 0.007853289 0.00000000       1
4      MOE              WoodCategory 0.005828345 0.00000000       1
5      MOE              LeimgradCode 0.171592848 0.00000000       1
6      MOE WoodCategory:LeimgradCode 0.020441122 0.00000000       1
7       IB              WoodCategory 0.063867409 0.00000000       1
8       IB              LeimgradCode 0.641529646 0.36548957       1
9       IB WoodCategory:LeimgradCode 0.023267981 0.00000000       1

5. Post-hoc Analysis Results:

Post-hoc Results for IB :
# A tibble: 6 x 8
  .y.   group1        group2        estimate conf.low conf.high p.adj p.adj.signif
* <chr> <chr>         <chr>            <dbl>    <dbl>     <dbl> <dbl> <chr>
1 Value Hardwood.high Softwood.high   0.0375   -0.406    0.481  0.992 ns
2 Value Hardwood.high Hardwood.low   -0.503    -0.848   -0.158  0.006 **
3 Value Hardwood.high Softwood.low   -0.357    -0.773    0.0582 0.093 ns
4 Value Softwood.high Hardwood.low   -0.541    -0.967   -0.115  0.019 *
5 Value Softwood.high Softwood.low   -0.395    -0.865    0.0749 0.096 ns
6 Value Hardwood.low  Softwood.low    0.146    -0.245    0.537  0.6   ns

Post-hoc Results for MOE :
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Value ~ WoodCategory * LeimgradCode, data = data_subset)

```

```
$WoodCategory
                  diff       lwr      upr     p adj
Softwood-Hardwood  -50  -396.0864 296.0864 0.7633498

$LeimgradCode
           diff      lwr      upr     p adj
low-high -291.2 -630.294 47.89404 0.0874407

$`WoodCategory:LeimgradCode`
                                diff       lwr      upr     p adj
Softwood:high-Hardwood:high -144.33333 -804.8807 516.2140 0.9224802
Hardwood:low-Hardwood:high  -366.66667 -957.4782 224.1448 0.3201132
Softwood:low-Hardwood:high  -322.33333 -982.8807 338.2140 0.5194356
Hardwood:low-Softwood:high  -222.33333 -882.8807 438.2140 0.7718313
Softwood:low-Softwood:high  -178.00000 -901.5934 545.5934 0.8941013
Softwood:low-Hardwood:low     44.33333 -616.2140 704.8807 0.9973831


Post-hoc Results for MOR :
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Value ~ WoodCategory * LeimgradCode, data = data_subset)

$WoodCategory
                       diff       lwr      upr     p adj
Softwood-Hardwood -2.616667 -6.885762 1.652428 0.2122325

$LeimgradCode
          diff       lwr        upr     p adj
low-high -5.11 -9.292842 -0.9271583 0.0197456

$`WoodCategory:LeimgradCode`
                               diff       lwr       upr     p adj
Softwood:high-Hardwood:high -3.333333 -11.48141 4.8147457 0.6531607
Hardwood:low-Hardwood:high  -5.683333 -12.97120 1.6045301 0.1569939
Softwood:low-Hardwood:high  -7.583333 -15.73141 0.5647457 0.0727415
Hardwood:low-Softwood:high  -2.350000 -10.49808 5.7980790 0.8417693
Softwood:low-Softwood:high  -4.250000 -13.17577 4.6757734 0.5392044
Softwood:low-Hardwood:low   -1.900000 -10.04808 6.2480790 0.9078990


6. Descriptive Statistics:
# A tibble: 12 x 9
   Property WoodCategory LeimgradCode     n    mean     sd      se ci_lower ci_upper
   <chr>    <chr>        <chr>        <int>   <dbl>  <dbl>   <dbl>    <dbl>    <dbl>
 1 IB       Hardwood     high             6    1.10  0.218  0.0889    0.866     1.32
 2 IB       Hardwood     low              6   0.592  0.164  0.0669    0.420    0.764
 3 IB       Softwood     high             4    1.13  0.200  0.100     0.814     1.45
 4 IB       Softwood     low              4   0.738  0.182  0.0912    0.447     1.03
 5 MOE      Hardwood     high             6 3911.  414.   169.     3476.    4345.
 6 MOE      Hardwood     low              6 3544.  391.   160.     3134.    3955.
 7 MOE      Softwood     high             4 3766.  373.   186.     3173.    4360.
 8 MOE      Softwood     low              4 3588.   49.0   24.5    3511.    3666.
 9 MOR      Hardwood     high             6   28.7    5.45    2.22     23.0     34.5
10 MOR      Hardwood     low              6   23.0    4.99    2.04     17.8     28.3
11 MOR      Softwood     high             4   25.4    2.36    1.18     21.6     29.2
12 MOR      Softwood     low              4   21.2    2.68    1.34     16.9     25.4
```

Code 3. Anova results of Wood type and PMDI-content on mechanical property

```
*****************************************************************
# Wood Type & PMDI Level Influence on water resistance properties
-----------------------------------------------------------------
1. Normality Test Results (Shapiro-Wilk):
# A tibble: 16 x 7
   LeimgradCode WoodCategory Property variable statistic       p Normality
   <chr>        <chr>        <chr>    <chr>        <dbl>   <dbl> <chr>
 1 high         Hardwood     Quell24h Value        0.936 0.629   Normal
 2 low          Hardwood     Quell24h Value        0.674 0.00327 Non-normal
 3 high         Softwood     Quell24h Value        0.767 0.0555  Normal
 4 low          Softwood     Quell24h Value        0.748 0.0373  Non-normal
 5 high         Hardwood     Quell2h  Value        0.800 0.0587  Normal
 6 low          Hardwood     Quell2h  Value        0.637 0.00125 Non-normal
 7 high         Softwood     Quell2h  Value        0.745 0.0344  Non-normal
 8 low          Softwood     Quell2h  Value        0.750 0.0389  Non-normal
 9 high         Hardwood     WA24h    Value        0.717 0.00932 Non-normal
10 low          Hardwood     WA24h    Value        0.689 0.00475 Non-normal
11 high         Softwood     WA24h    Value        0.762 0.0501  Normal
12 low          Softwood     WA24h    Value        0.785 0.0774  Normal
13 high         Hardwood     WA2h     Value        0.829 0.105   Normal
14 low          Hardwood     WA2h     Value        0.710 0.00783 Non-normal
15 high         Softwood     WA2h     Value        0.760 0.0473  Non-normal
16 low          Softwood     WA2h     Value        0.771 0.0593  Normal

2. Homogeneity of Variance Test Results (Levene's Test):
# A tibble: 4 x 3
  Property levene_test      Homogeneity
  <chr>    <list>           <chr>
```



(a) Normal QQ-plot

(b) Interaction effects of wood type and resine content

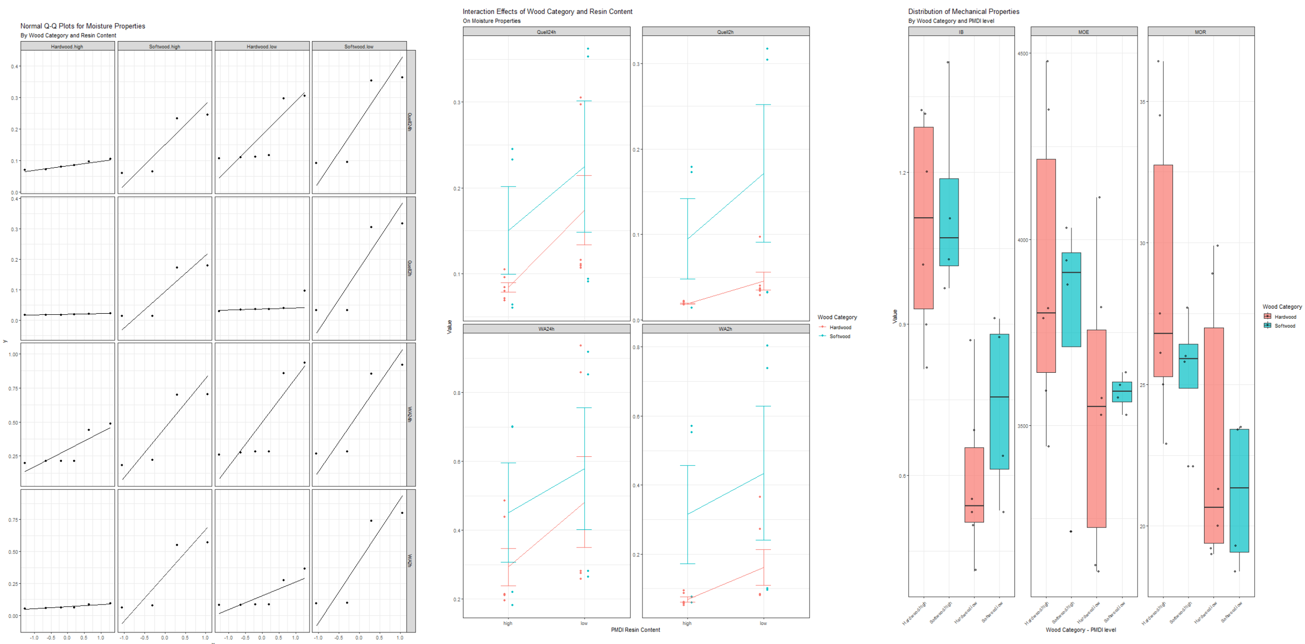
(c) Distribution of the water resistant property

Figure 3. Analysis of effects of Wood type and PMDI-content on mechanical property

```
1 Quell24h <anova [2 x 3]> Non-homogeneous
2 Quell2h  <anova [2 x 3]> Non-homogeneous
3 WA24h    <anova [2 x 3]> Homogeneous
4 WA2h     <anova [2 x 3]> Non-homogeneous

3. Analysis Results:

Results for Quell24h :

        One-way analysis of means (not assuming equal variances)

data:  Value and interaction(WoodCategory, LeimgradCode)
F = 2.6487, num df = 3.0000, denom df = 5.9004, p-value = 0.1446


Results for Quell2h :

        One-way analysis of means (not assuming equal variances)

data:  Value and interaction(WoodCategory, LeimgradCode)
F = 3.3814, num df = 3.0000, denom df = 5.7831, p-value = 0.09831


Results for WA24h :
                          Df Sum Sq Mean Sq F value Pr(>F)
WoodCategory               1 0.0783 0.07834   1.013  0.329
LeimgradCode               1 0.1353 0.13530   1.750  0.205
WoodCategory:LeimgradCode  1 0.0044 0.00444   0.057  0.814
Residuals                 16 1.2373 0.07733

Results for WA2h :

        One-way analysis of means (not assuming equal variances)

data:  Value and interaction(WoodCategory, LeimgradCode)
F = 2.6069, num df = 3.0000, denom df = 5.8378, p-value = 0.1492


4. Effect Sizes Results:
   Property                 Parameter Eta_squared     CI_low CI_high
1   Quell2h              WoodCategory 0.313446336 0.04198770       1
2   Quell2h              LeimgradCode 0.091132214 0.00000000       1
3   Quell2h WoodCategory:LeimgradCode 0.027653674 0.00000000       1
4  Quell24h              WoodCategory 0.098359269 0.00000000       1
5  Quell24h              LeimgradCode 0.188650651 0.00000000       1
6  Quell24h WoodCategory:LeimgradCode 0.001905499 0.00000000       1
7      WA2h              WoodCategory 0.293149740 0.03138505       1
8      WA2h              LeimgradCode 0.064400075 0.00000000       1
9      WA2h WoodCategory:LeimgradCode 0.001113901 0.00000000       1
10    WA24h              WoodCategory 0.059542150 0.00000000       1
11    WA24h              LeimgradCode 0.098572287 0.00000000       1
12    WA24h WoodCategory:LeimgradCode 0.003576273 0.00000000       1
```

```

5. Post-hoc Analysis Results:

Post-hoc Results for Quell24h :
# A tibble: 6 x 8
  .y.   group1        group2        estimate conf.low conf.high p.adj p.adj.signif
* <chr> <chr>         <chr>            <dbl>    <dbl>     <dbl> <dbl> <chr>
1 Value Hardwood_high Hardwood_low    0.09     -0.0574    0.237 0.233 ns
2 Value Hardwood_high Softwood_high   0.0663   -0.178     0.311 0.624 ns
3 Value Hardwood_high Softwood_low    0.141    -0.227     0.508 0.404 ns
4 Value Hardwood_low  Softwood_high  -0.0237   -0.245     0.197 0.982 ns
5 Value Hardwood_low  Softwood_low    0.0508   -0.277     0.379 0.931 ns
6 Value Softwood_high Softwood_low    0.0745   -0.259     0.408 0.848 ns

Post-hoc Results for Quell2h :
# A tibble: 6 x 8
  .y.   group1        group2        estimate conf.low conf.high p.adj p.adj.signif
* <chr> <chr>         <chr>            <dbl>    <dbl>     <dbl> <dbl> <chr>
1 Value Hardwood_high Hardwood_low    0.0262   -0.0122   0.0645 0.172 ns
2 Value Hardwood_high Softwood_high   0.0757   -0.150    0.301  0.484 ns
3 Value Hardwood_high Softwood_low    0.152    -0.235    0.540  0.386 ns
4 Value Hardwood_low  Softwood_high   0.0495   -0.168    0.267  0.745 ns
5 Value Hardwood_low  Softwood_low    0.126    -0.256    0.508  0.506 ns
6 Value Softwood_high Softwood_low    0.0765   -0.271    0.424  0.842 ns

Post-hoc Results for WA24h :
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Value ~ WoodCategory * LeimgradCode, data = data_subset)

$WoodCategory
                     diff        lwr       upr     p adj
Softwood-Hardwood 0.12775 -0.1413259 0.3968259 0.3291672

$LeimgradCode
           diff         lwr       upr     p adj
low-high 0.1645 -0.09913945 0.4281394 0.2045197

$`WoodCategory:LeimgradCode`
                                diff        lwr       upr     p adj
Softwood:high-Hardwood:high 0.15816667 -0.3553969 0.6717302 0.8145433
Hardwood:low-Hardwood:high  0.18883333 -0.2705119 0.6481785 0.6497689
Softwood:low-Hardwood:high  0.28616667 -0.2273969 0.7997302 0.4092554
Hardwood:low-Softwood:high  0.03066667 -0.4828969 0.5442302 0.9981507
Softwood:low-Softwood:high  0.12800000 -0.4345807 0.6905807 0.9136799
Softwood:low-Hardwood:low   0.09733333 -0.4162302 0.6108969 0.9473008


Post-hoc Results for WA2h :
# A tibble: 6 x 8
  .y.   group1        group2        estimate conf.low conf.high p.adj p.adj.signif
* <chr> <chr>         <chr>            <dbl>    <dbl>     <dbl> <dbl> <chr>
1 Value Hardwood_high Hardwood_low    0.0928   -0.0959    0.282 0.373 ns
2 Value Hardwood_high Softwood_high   0.246    -0.440     0.932 0.443 ns
3 Value Hardwood_high Softwood_low    0.366    -0.573     1.30  0.391 ns
4 Value Hardwood_low  Softwood_high   0.153    -0.481     0.787 0.754 ns
5 Value Hardwood_low  Softwood_low    0.273    -0.620     1.17  0.588 ns
6 Value Softwood_high Softwood_low    0.120    -0.740     0.980 0.957 ns

6. Descriptive Statistics:
# A tibble: 16 x 9
   Property WoodCategory LeimgradCode     n   mean      sd       se ci_lower ci_upper
   <chr>    <chr>        <chr>        <int>  <dbl>   <dbl>    <dbl>    <dbl>    <dbl>
 1 Quell24h Hardwood     high             6 0.0842 0.0141  0.00576   0.0694   0.0990
 2 Quell24h Hardwood     low              6 0.174  0.0983  0.0401    0.0710   0.277
 3 Quell24h Softwood     high             4 0.150  0.102   0.0512   -0.0123   0.313
 4 Quell24h Softwood     low              4 0.225  0.153   0.0765   -0.0185   0.469
 5 Quell2h  Hardwood     high             6 0.0193 0.00175 0.000715  0.0175   0.0212
 6 Quell2h  Hardwood     low              6 0.0455 0.0255  0.0104    0.0187   0.0723
 7 Quell2h  Softwood     high             4 0.095  0.0936  0.0468   -0.0539   0.244
 8 Quell2h  Softwood     low              4 0.172  0.161   0.0803   -0.0840   0.427
 9 WA24h    Hardwood     high             6 0.293  0.132   0.0541    0.154    0.432
10 WA24h    Hardwood     low              6 0.482  0.323   0.132     0.143    0.821
11 WA24h    Softwood     high             4 0.451  0.289   0.145    -0.00901  0.911
12 WA24h    Softwood     low              4 0.579  0.354   0.177     0.0150   1.14
13 WA2h     Hardwood     high             6 0.0687 0.0178  0.00725   0.0500   0.0873
14 WA2h     Hardwood     low              6 0.162  0.126   0.0514    0.0294   0.294
15 WA2h     Softwood     high             4 0.315  0.285   0.143    -0.139    0.768
16 WA2h     Softwood     low              4 0.434  0.389   0.195    -0.185    1.05
```

Code 4. Anova results of Wood type and PMDI-content on water resistant property



(a) Normal QQ-plot

(b) Interaction effects of wood type and resine content

(c) Distribution of the water resistant property

Figure 4. Analysis of effects of Wood type and PMDI-content on water resistant property

4.5. UF and PMDI-Bonded Particleboard Comparison

In this subsection three-way ANOVA was used to evaluate the effects of resin type (UF and PMDI), resin content, and wood type on three key mechanical properties of particleboard: modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB). Data quality verification was conducted using two critical tests: Shapiro-Wilk normality test, which showed that all experimental combinations except for the MOR values of the PMDI low-content hardwood group conformed to the normality assumption ($p > 0.05$); and Levene's test for homogeneity of variance, which indicated that MOE and MOR met the assumption of homogeneous variance, while IB exhibited heteroscedasticity. Based on these foundational assumption tests, different statistical methods were applied: traditional three-way ANOVA for MOE and MOR which satisfied variance homogeneity, and the more robust Type III SS ANOVA for IB.

The analysis revealed that MOR performance was significantly influenced by resin type ($p < 0.001$), content ($p < 0.001$), and wood type ($p < 0.05$), with effect size analysis showing resin content had the strongest effect ($\eta^2 = 0.39$), followed by resin type ($\eta^2 = 0.30$). MOE performance analysis demonstrated that resin type and content exhibited similar effect sizes ($\eta^2 \approx 0.30$) and both had significant influences ($p < 0.001$), while wood type's effect was not significant. IB performance was primarily affected by resin content, showing the largest effect size ($\eta^2 = 0.68$) and highly significant statistical difference ($p < 0.001$), with a marginally significant interaction observed between resin type and content ($p < 0.1$).

The findings revealed that PMDI resin significantly outperformed UF resin in strength properties (MOR and MOE); higher resin content consistently showed superior performance across all mechanical properties; and hardwood only demonstrated a slight advantage in MOR. Notably, except for the marginally significant interaction between resin type and content observed in IB, few significant interactions were found among other factors, indicating relatively independent effects of these factors. Box plot analysis further demonstrated that under the same content level, PMDI resin combinations generally exhibited better mechanical properties, with performance advantages being particularly pronounced under high-content conditions.

The study also analyzed the effects of resin type (UF and PMDI), resin content, and wood type on the moisture resistance of particleboard, with assessment indicators including thickness swelling at 24 hours and 2 hours (Quell24h, Quell2h) and water absorption (WA24h, WA2h). In data quality tests, the Shapiro-Wilk normality test revealed that multiple level combinations of PMDI treatment groups deviated from normal distribution, particularly under low content conditions; Levene's test indicated that all water resistance indicators failed to meet the homogeneity of variance assumption. Based on these test results, the more robust Type III SS ANOVA method was employed.

From a temporal perspective, short-term (2-hour) water absorption (WA2h) was significantly influenced by resin type ($p < 0.01$), wood type ($p < 0.05$), and the interaction between resin type and content ($p < 0.05$, $\eta^2 = 0.30$), while thickness swelling (Quell2h) showed only marginal significance in wood type ($p < 0.1$). Long-term (24-hour) water absorption (WA24h) was primarily affected by resin type, showing the most significant effect ($p < 0.01$, $\eta^2 = 0.53$); thickness swelling (Quell24h) showed marginal significance only in resin content and its interaction with resin type ($p < 0.1$).

Further analysis revealed that resin type had the most significant impact, with PMDI demonstrating superior water resistance compared to UF, especially under long-term water exposure conditions; the influence of resin content was mainly manifested through interactions with other factors, with high content conditions generally showing better water resistance; the effect of wood type was primarily reflected in short-term water absorption, where hardwood showed notable advantages - under PMDI conditions, the water absorption rate of the hardwood group at high content (0.0687) was significantly lower than the softwood group (0.315), maintaining a similar trend at low content (hardwood 0.162 vs softwood 0.434). These findings indicate that: for scenarios requiring high long-term water resistance, PMDI resin should be prioritized; for applications demanding high short-term water resistance, hardwood substrate can provide better performance assurance; additionally, adopting high-content resin strategies when feasible can further enhance the overall water resistance of the material.

4.6. Three-way ANOVA results for UF and PMDI-Bonded Comparison

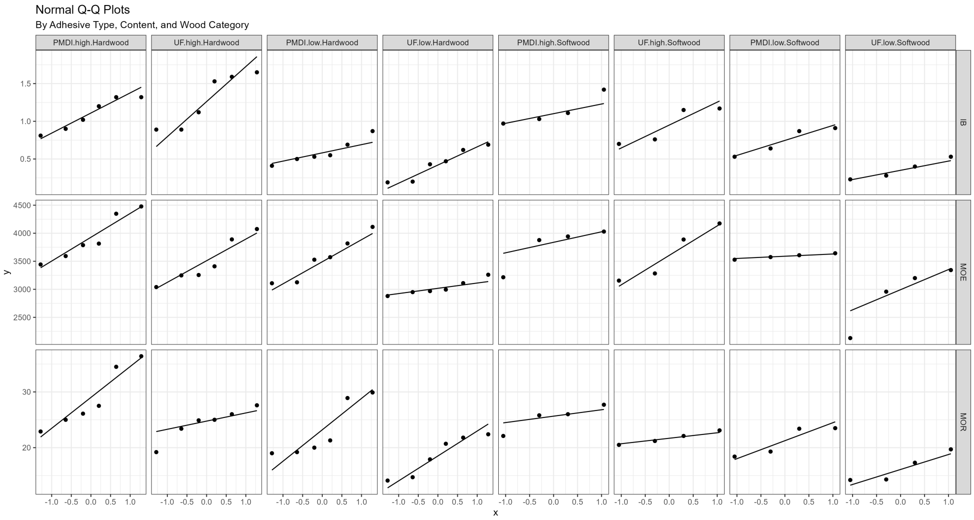
```
=================================================================
THREE-WAY ANOVA ANALYSIS OF MECHANICAL PROPERTIES
=================================================================
1. Normality Test Results (Shapiro-Wilk):
-------------------------------------------
   LeimCode LeimgradCode WoodCategory Property variable statistic          p  Normality
1      PMDI         high     Hardwood       IB    Value 0.8988695 0.36729086     Normal
2      PMDI         high     Softwood       IB    Value 0.8665848 0.28449818     Normal
3      PMDI          low     Hardwood       IB    Value 0.9181438 0.49209357     Normal
4      PMDI          low     Softwood       IB    Value 0.8976322 0.41939348     Normal
5        UF         high     Hardwood       IB    Value 0.8321539 0.11209187     Normal
6        UF         high     Softwood       IB    Value 0.8050032 0.11149940     Normal
7        UF          low     Hardwood       IB    Value 0.9093340 0.43202950     Normal
8        UF          low     Softwood       IB    Value 0.9505417 0.71950121     Normal
9      PMDI         high     Hardwood      MOE    Value 0.9032501 0.39349747     Normal
10     PMDI         high     Softwood      MOE    Value 0.7813707 0.07279304     Normal
11     PMDI          low     Hardwood      MOE    Value 0.9319642 0.59535344     Normal
12     PMDI          low     Softwood      MOE    Value 0.9932421 0.97343818     Normal
13       UF         high     Hardwood      MOE    Value 0.8953564 0.34721000     Normal
14       UF         high     Softwood      MOE    Value 0.9057111 0.45997620     Normal
15       UF          low     Hardwood      MOE    Value 0.9123031 0.45172058     Normal
16       UF          low     Softwood      MOE    Value 0.8656166 0.28083392     Normal
17     PMDI         high     Hardwood      MOR    Value 0.8862775 0.29914044     Normal
18     PMDI         high     Softwood      MOR    Value 0.9023662 0.44290704     Normal
19     PMDI          low     Hardwood      MOR    Value 0.7772014 0.03629348 Non-normal
20     PMDI          low     Softwood      MOR    Value 0.8127583 0.12713931     Normal
21       UF         high     Hardwood      MOR    Value 0.9097413 0.43469658     Normal
22       UF         high     Softwood      MOR    Value 0.9849982 0.93064637     Normal
23       UF          low     Hardwood      MOR    Value 0.8826615 0.28150339     Normal
24       UF          low     Softwood      MOR    Value 0.8740672 0.31391584     Normal
*******************************************
2. Homogeneity of Variance Test Results (Levene's Test):
-------------------------------------------
# A tibble: 3 x 3
  Property levene_test     Homogeneity
  <chr>    <list>          <chr>
1 IB       <anova [2 x 3]> Non-homogeneous
2 MOE      <anova [2 x 3]> Homogeneous
3 MOR      <anova [2 x 3]> Homogeneous
*******************************************
THREE-WAY ANOVA RESULTS
=================================================================
Results for MOR :
-------------------------------------------
                                  Df Sum Sq Mean Sq F value   Pr(>F)
LeimCode                           1  188.4  188.36  13.615  0.00083 ***
LeimgradCode                       1  286.2  286.23  20.690 7.34e-05 ***
WoodCategory                       1   61.0   61.00   4.410  0.04371 *
LeimCode:LeimgradCode              1    0.6    0.58   0.042  0.83961
LeimCode:WoodCategory              1    0.1    0.09   0.006  0.93687
LeimgradCode:WoodCategory          1    2.0    2.02   0.146  0.70513
LeimCode:LeimgradCode:WoodCategory 1    0.6    0.64   0.046  0.83098
Residuals                         32  442.7   13.83
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Results for MOE :
-------------------------------------------
                                  Df  Sum Sq Mean Sq F value   Pr(>F)
LeimCode                           1 1996749 1996749  14.022 0.000714 ***
LeimgradCode                       1 1822009 1822009  12.795 0.001130 **
WoodCategory                       1    3888    3888   0.027 0.869794
LeimCode:LeimgradCode              1  184009  184009   1.292 0.264082
LeimCode:WoodCategory              1    8568    8568   0.060 0.807794
LeimgradCode:WoodCategory          1    2912    2912   0.020 0.887184
LeimCode:LeimgradCode:WoodCategory 1  119885  119885   0.842 0.365718
Residuals                         32 4556763  142399
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Results for IB :
-------------------------------------------
Anova Table (Type III tests)

Response: Value
                                  Sum Sq Df  F value    Pr(>F)
(Intercept)                       7.1942  1 137.6130 3.977e-13 ***
```

```
LeimCode                             0.1008  1   1.9288 0.1744824
LeimgradCode                         0.7600  1  14.5383 0.0005906 ***
WoodCategory                         0.0034  1   0.0646 0.8010565
LeimCode:LeimgradCode                0.1751  1   3.3495 0.0765553 .
LeimCode:WoodCategory                0.1650  1   3.1566 0.0851294 .
LeimgradCode:WoodCategory            0.0141  1   0.2694 0.6073109
LeimCode:LeimgradCode:WoodCategory   0.0138  1   0.2640 0.6109122
Residuals                            1.6729 32
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
*****************************************************************
EFFECT SIZES
=================================================================
   Property                          Parameter Partial_Eta_squared      CI_low CI_high
1       MOR                           LeimCode        0.2984829909 0.096994863       1
2       MOR                       LeimgradCode        0.3926735689 0.177504100       1
3       MOR                       WoodCategory        0.1211139071 0.001977026       1
4       MOR              LeimCode:LeimgradCode        0.0012994504 0.000000000       1
5       MOR              LeimCode:WoodCategory        0.0001991223 0.000000000       1
6       MOR          LeimgradCode:WoodCategory        0.0045348414 0.000000000       1
7       MOR LeimCode:LeimgradCode:WoodCategory        0.0014451269 0.000000000       1
8       MOE                           LeimCode        0.3046838176 0.101728942       1
9       MOE                       LeimgradCode        0.2856363365 0.087459293       1
10      MOE                       WoodCategory        0.0008525427 0.000000000       1
11      MOE              LeimCode:LeimgradCode        0.0388141854 0.000000000       1
12      MOE              LeimCode:WoodCategory        0.0018767860 0.000000000       1
13      MOE          LeimgradCode:WoodCategory        0.0006386566 0.000000000       1
14      MOE LeimCode:LeimgradCode:WoodCategory        0.0256348952 0.000000000       1
15       IB                           LeimCode        0.0623822128 0.000000000       1
16       IB                       LeimgradCode        0.6830970074 0.520525565       1
17       IB                       WoodCategory        0.0175746993 0.000000000       1
18       IB              LeimCode:LeimgradCode        0.1055457606 0.000000000       1
19       IB              LeimCode:WoodCategory        0.1109918374 0.000000000       1
20       IB          LeimgradCode:WoodCategory        0.0464011796 0.000000000       1
21       IB LeimCode:LeimgradCode:WoodCategory        0.0081826365 0.000000000       1

POST-HOC ANALYSIS RESULTS
=================================================================
Post-hoc Results for MOR :
------------------------------------------
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Value ~ LeimCode * LeimgradCode * WoodCategory, data = data_subset)

$LeimCode
         diff       lwr       upr     p adj
UF-PMDI -4.34 -6.735802 -1.944198 0.0008296

$LeimgradCode
          diff       lwr       upr    p adj
low-high -5.35 -7.745802 -2.954198 7.34e-05

$WoodCategory
                       diff       lwr         upr     p adj
Softwood-Hardwood -2.520833 -4.966038 -0.07562847 0.0437067

$`LeimCode:LeimgradCode`
                    diff        lwr         upr     p adj
UF:high-PMDI:high  -4.10  -8.606673  0.40667281 0.0851475
PMDI:low-PMDI:high -5.11  -9.616673 -0.60332719 0.0213363
UF:low-PMDI:high   -9.69 -14.196673 -5.18332719 0.0000104
PMDI:low-UF:high   -1.01  -5.516673  3.49667281 0.9290438
UF:low-UF:high     -5.59 -10.096673 -1.08332719 0.0103724
UF:low-PMDI:low    -4.58  -9.086673 -0.07332719 0.0452514

$`LeimCode:WoodCategory`
                                diff        lwr        upr     p adj
UF:Hardwood-PMDI:Hardwood   -4.416667  -8.530677 -0.3026561 0.0315754
PMDI:Softwood-PMDI:Hardwood -2.616667  -7.216270  1.9829370 0.4256163
UF:Softwood-PMDI:Hardwood   -6.841667 -11.441270 -2.2420630 0.0017445
PMDI:Softwood-UF:Hardwood    1.800000  -2.799604  6.3996037 0.7156580
UF:Softwood-UF:Hardwood     -2.425000  -7.024604  2.1746037 0.4914699
UF:Softwood-PMDI:Softwood   -4.225000  -9.263613  0.8136134 0.1260943

$`LeimgradCode:WoodCategory`
                                diff        lwr        upr     p adj
low:Hardwood-high:Hardwood  -5.716667  -9.830677 -1.6026561 0.0035893
high:Softwood-high:Hardwood -2.979167  -7.578770  1.6204370 0.3132487
low:Softwood-high:Hardwood  -7.779167 -12.378770 -3.1795630 0.0003715
high:Softwood-low:Hardwood   2.737500  -1.862104  7.3371037 0.3861645
low:Softwood-low:Hardwood   -2.062500  -6.662104  2.5371037 0.6221365
low:Softwood-high:Softwood  -4.800000  -9.838613  0.2386134 0.0664207

$`LeimCode:LeimgradCode:WoodCategory`
                                          diff         lwr        upr     p adj
UF:high:Hardwood-PMDI:high:Hardwood  -4.383333 -11.3394103  2.5727436 0.4719137
PMDI:low:Hardwood-PMDI:high:Hardwood -5.683333 -12.6394103  1.2727436 0.1767109
UF:low:Hardwood-PMDI:high:Hardwood  -10.133333 -17.0894103 -3.1772564 0.0010496
PMDI:high:Softwood-PMDI:high:Hardwood -3.333333 -11.1104638  4.4437971 0.8557949
UF:high:Softwood-PMDI:high:Hardwood  -7.008333 -14.7854638  0.7687971 0.1019629
```

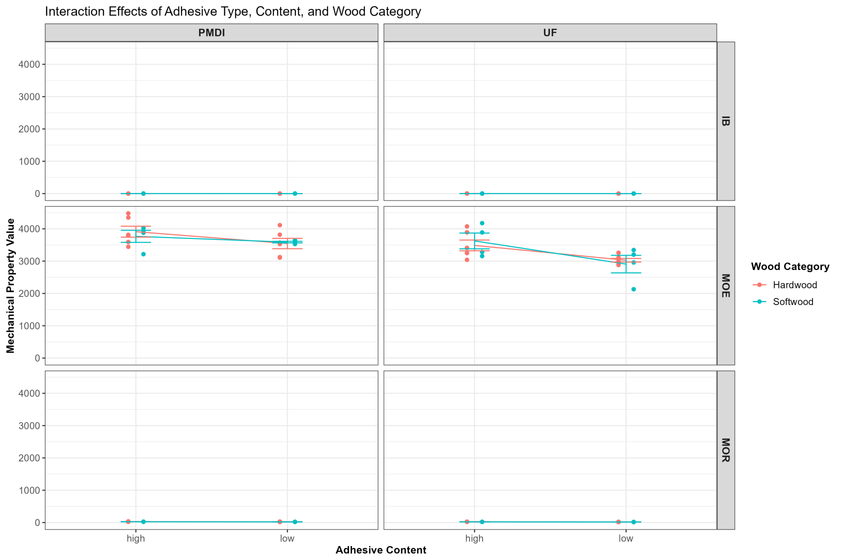
```
PMDI:low:Softwood-PMDI:high:Hardwood    -7.583333 -15.3604638  0.1937971 0.0601979
UF:low:Softwood-PMDI:high:Hardwood     -12.358333 -20.1354638 -4.5812029 0.0003134
PMDI:low:Hardwood-UF:high:Hardwood      -1.300000  -8.2560770  5.6560770 0.9985562
UF:low:Hardwood-UF:high:Hardwood        -5.750000 -12.7060770  1.2060770 0.1664711
PMDI:high:Softwood-UF:high:Hardwood      1.050000  -6.7271305  8.8271305 0.9998277
UF:high:Softwood-UF:high:Hardwood       -2.625000 -10.4021305  5.1521305 0.9536128
PMDI:low:Softwood-UF:high:Hardwood      -3.200000 -10.9771305  4.5771305 0.8793546
UF:low:Softwood-UF:high:Hardwood        -7.975000 -15.7521305 -0.1978695 0.0412123
UF:low:Hardwood-PMDI:low:Hardwood       -4.450000 -11.4060770  2.5060770 0.4529413
PMDI:high:Softwood-PMDI:low:Hardwood     2.350000  -5.4271305 10.1271305 0.9742895
UF:high:Softwood-PMDI:low:Hardwood      -1.325000  -9.1021305  6.4521305 0.9992036
PMDI:low:Softwood-PMDI:low:Hardwood     -1.900000  -9.6771305  5.8771305 0.9924168
UF:low:Softwood-PMDI:low:Hardwood       -6.675000 -14.4521305  1.1021305 0.1359089
PMDI:high:Softwood-UF:low:Hardwood       6.800000  -0.9771305 14.5771305 0.1222288
UF:high:Softwood-UF:low:Hardwood         3.125000  -4.6521305 10.9021305 0.8915713
PMDI:low:Softwood-UF:low:Hardwood        2.550000  -5.2271305 10.3271305 0.9601177
UF:low:Softwood-UF:low:Hardwood         -2.225000 -10.0021305  5.5521305 0.9810275
UF:high:Softwood-PMDI:high:Softwood     -3.675000 -12.1944196  4.8444196 0.8517867
PMDI:low:Softwood-PMDI:high:Softwood    -4.250000 -12.7694196  4.2694196 0.7375612
UF:low:Softwood-PMDI:high:Softwood      -9.025000 -17.5444196 -0.5055804 0.0316789
PMDI:low:Softwood-UF:high:Softwood      -0.575000  -9.0944196  7.9444196 0.9999985
UF:low:Softwood-UF:high:Softwood        -5.350000 -13.8694196  3.1694196 0.4762404
UF:low:Softwood-PMDI:low:Softwood       -4.775000 -13.2944196  3.7444196 0.6146609
*******************************************
Post-hoc Results for MOE :
-------------------------------------------
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Value ~ LeimCode * LeimgradCode * WoodCategory, data = data_subset)

$LeimCode
           diff       lwr       upr     p adj
UF-PMDI -446.85 -689.9193 -203.7807 0.0007135

$LeimgradCode
            diff       lwr       upr   p adj
low-high -426.85 -669.9193 -183.7807 0.00113

$WoodCategory
                     diff       lwr      upr     p adj
Softwood-Hardwood -20.125 -268.2065 227.9565 0.8697937

$`LeimCode:LeimgradCode`
                     diff        lwr       upr     p adj
UF:high-PMDI:high  -311.2  -768.4305  146.0305 0.2721230
PMDI:low-PMDI:high -291.2  -748.4305  166.0305 0.3275607
UF:low-PMDI:high   -873.7 -1330.9305 -416.4695 0.0000675
PMDI:low-UF:high     20.0  -437.2305  477.2305 0.9993918
UF:low-UF:high     -562.5 -1019.7305 -105.2695 0.0111265
UF:low-PMDI:low    -582.5 -1039.7305 -125.2695 0.0082063

$`LeimCode:WoodCategory`
                               diff        lwr        upr     p adj
UF:Hardwood-PMDI:Hardwood   -470.75 -888.14246 -53.357536 0.0222030
PMDI:Softwood-PMDI:Hardwood  -50.00 -516.65896 416.658962 0.9913134
UF:Softwood-PMDI:Hardwood   -461.00 -927.65896   5.658962 0.0538214
PMDI:Softwood-UF:Hardwood    420.75  -45.90896 887.408962 0.0891701
UF:Softwood-UF:Hardwood        9.75 -456.90896 476.408962 0.9999334
UF:Softwood-PMDI:Softwood   -411.00 -922.19928 100.199280 0.1510668

$`LeimgradCode:WoodCategory`
                                   diff        lwr        upr     p adj
low:Hardwood-high:Hardwood  -412.916667 -830.30913   4.475798 0.0533664
high:Softwood-high:Hardwood   -2.708333 -469.36730 463.950629 0.9999986
low:Softwood-high:Hardwood  -450.458333 -917.11730  16.200629 0.0616314
high:Softwood-low:Hardwood   410.208333  -56.45063 876.867295 0.1011830
low:Softwood-low:Hardwood    -37.541667 -504.20063 429.117295 0.9962677
low:Softwood-high:Softwood  -447.750000 -958.94928  63.449280 0.1029615

$`LeimCode:LeimgradCode:WoodCategory`
                                             diff         lwr         upr     p adj
UF:high:Hardwood-PMDI:high:Hardwood    -424.50000 -1130.23812  281.238121 0.5299571
PMDI:low:Hardwood-PMDI:high:Hardwood   -366.66667 -1072.40479  339.071455 0.6975796
UF:low:Hardwood-PMDI:high:Hardwood     -883.66667 -1589.40479 -177.928545 0.0064378
PMDI:high:Softwood-PMDI:high:Hardwood  -144.33333  -933.37254  644.705873 0.9987411
UF:high:Softwood-PMDI:high:Hardwood    -285.58333 -1074.62254  503.455873 0.9339840
PMDI:low:Softwood-PMDI:high:Hardwood   -322.33333 -1111.37254  466.705873 0.8831708
UF:low:Softwood-PMDI:high:Hardwood    -1003.08333 -1792.12254 -214.044127 0.0054555
PMDI:low:Hardwood-UF:high:Hardwood       57.83333  -647.90479  763.571455 0.9999942
UF:low:Hardwood-UF:high:Hardwood       -459.16667 -1164.90479  246.571455 0.4317325
PMDI:high:Softwood-UF:high:Hardwood     280.16667  -508.87254 1069.205873 0.9399764
UF:high:Softwood-UF:high:Hardwood       138.91667  -650.12254  927.955873 0.9990154
PMDI:low:Softwood-UF:high:Hardwood      102.16667  -686.87254  891.205873 0.9998697
UF:low:Softwood-UF:high:Hardwood       -578.58333 -1367.62254  210.455873 0.2871179
UF:low:Hardwood-PMDI:low:Hardwood      -517.00000 -1222.73812  188.738121 0.2882156
PMDI:high:Softwood-PMDI:low:Hardwood    222.33333  -566.70587 1011.372540 0.9825890
UF:high:Softwood-PMDI:low:Hardwood       81.08333  -707.95587  870.122540 0.9999726
PMDI:low:Softwood-PMDI:low:Hardwood      44.33333  -744.70587  833.372540 0.9999996
UF:low:Softwood-PMDI:low:Hardwood      -636.41667 -1425.45587  152.622540 0.1884317
PMDI:high:Softwood-UF:low:Hardwood      739.33333   -49.70587 1528.372540 0.0793353
```

```
UF:high:Softwood-UF:low:Hardwood         598.08333   -190.95587 1387.122540 0.2505724
PMDI:low:Softwood-UF:low:Hardwood        561.33333   -227.70587 1350.372540 0.3221664
UF:low:Softwood-UF:low:Hardwood         -119.41667   -908.45587  669.622540 0.9996327
UF:high:Softwood-PMDI:high:Softwood     -141.25000  -1005.59914  723.099144 0.9993926
PMDI:low:Softwood-PMDI:high:Softwood    -178.00000  -1042.34914  686.349144 0.9973344
UF:low:Softwood-PMDI:high:Softwood      -858.75000  -1723.09914    5.599144 0.0524907
PMDI:low:Softwood-UF:high:Softwood       -36.75000   -901.09914  827.599144 0.9999999
UF:low:Softwood-UF:high:Softwood        -717.50000  -1581.84914  146.849144 0.1628602
UF:low:Softwood-PMDI:low:Softwood       -680.75000  -1545.09914  183.599144 0.2111908
*******************************************
Post-hoc Results for IB :
-------------------------------------------
     .y.             group1              group2    estimate     conf.low   conf.high p.adj p.adj.signif
1  Value PMDI_high_Hardwood   UF_high_Hardwood  0.18333333 -0.480798546  0.84746521 0.945           ns
2  Value PMDI_high_Hardwood  PMDI_low_Hardwood -0.50333333 -0.927499012 -0.07916765 0.019            *
3  Value PMDI_high_Hardwood    UF_low_Hardwood -0.66166667 -1.122716968 -0.20061637 0.005           **
4  Value PMDI_high_Hardwood PMDI_high_Softwood  0.03750000 -0.512984137  0.58798414 1.000           ns
5  Value PMDI_high_Hardwood   UF_high_Softwood -0.15000000 -0.817198533  0.51719853 0.962           ns
6  Value PMDI_high_Hardwood  PMDI_low_Softwood -0.35750000 -0.872695872  0.15769587 0.224           ns
7  Value PMDI_high_Hardwood    UF_low_Softwood -0.73500000 -1.175522918 -0.29447708 0.002           **
8  Value   UF_high_Hardwood  PMDI_low_Hardwood -0.68666667 -1.339456814 -0.03387652 0.039            *
9  Value   UF_high_Hardwood    UF_low_Hardwood -0.84500000 -1.505722541 -0.18427746 0.013            *
10 Value   UF_high_Hardwood PMDI_high_Softwood -0.14583333 -0.842897979  0.55123131 0.985           ns
11 Value   UF_high_Hardwood   UF_high_Softwood -0.33333333 -1.090887648  0.42422098 0.665           ns
12 Value   UF_high_Hardwood  PMDI_low_Softwood -0.54083333 -1.222874552  0.14120789 0.140           ns
13 Value   UF_high_Hardwood    UF_low_Softwood -0.91833333 -1.577043083 -0.25962358 0.009           **
14 Value  PMDI_low_Hardwood    UF_low_Hardwood -0.15833333 -0.568094407  0.25142774 0.808           ns
15 Value  PMDI_low_Hardwood PMDI_high_Softwood  0.54083333  0.006632916  1.07503375 0.047            *
16 Value  PMDI_low_Hardwood   UF_high_Softwood  0.35333333 -0.321956373  1.02862304 0.364           ns
17 Value  PMDI_low_Hardwood  PMDI_low_Softwood  0.14583333 -0.342576497  0.63424316 0.875           ns
18 Value  PMDI_low_Hardwood    UF_low_Softwood -0.23166667 -0.612934611  0.14960128 0.336           ns
19 Value    UF_low_Hardwood PMDI_high_Softwood  0.69916667  0.154118795  1.24421454 0.014            *
20 Value    UF_low_Hardwood   UF_high_Softwood  0.51166667 -0.154821057  1.17815439 0.138           ns
21 Value    UF_low_Hardwood  PMDI_low_Softwood  0.30416667 -0.203671238  0.81200457 0.342           ns
22 Value    UF_low_Hardwood    UF_low_Softwood -0.07333333 -0.500931041  0.35426437 0.995           ns
23 Value PMDI_high_Softwood   UF_high_Softwood -0.18750000 -0.891848971  0.51684897 0.914           ns
24 Value PMDI_high_Softwood  PMDI_low_Softwood -0.39500000 -0.982876717  0.19287672 0.220           ns
25 Value PMDI_high_Softwood    UF_low_Softwood -0.77250000 -1.321732903 -0.22326710 0.012            *
26 Value   UF_high_Softwood  PMDI_low_Softwood -0.20750000 -0.899381943  0.48438194 0.853           ns
27 Value   UF_high_Softwood    UF_low_Softwood -0.58500000 -1.270107207  0.10010721 0.088           ns
28 Value  PMDI_low_Softwood    UF_low_Softwood -0.37750000 -0.883578143  0.12857814 0.150           ns
************************************************************
DESCRIPTIVE STATISTICS
============================================================
   Property LeimCode LeimgradCode WoodCategory n         mean          sd           se     ci_lower     ci_upper
1        IB     PMDI         high     Hardwood 6    1.0950000   0.2177843   0.08891007    0.8664494    1.3235506
2        IB     PMDI         high     Softwood 4    1.1325000   0.2000625   0.10003125    0.8141559    1.4508441
3        IB     PMDI          low     Hardwood 6    0.5916667   0.1637580   0.06685390    0.4198132    0.7635201
4        IB     PMDI          low     Softwood 4    0.7375000   0.1824600   0.09123002    0.4471654    1.0278346
5        IB       UF         high     Hardwood 6    1.2783333   0.3536335   0.14437028    0.9072177    1.6494490
6        IB       UF         high     Softwood 4    0.9450000   0.2495997   0.12479984    0.5478312    1.3421688
7        IB       UF          low     Hardwood 6    0.4333333   0.2077178   0.08480042    0.2153469    0.6513198
8        IB       UF          low     Softwood 4    0.3600000   0.1339154   0.06695770    0.1469107    0.5730893
9       MOE     PMDI         high     Hardwood 6 3910.8333333 413.9929549 169.01191608 3476.3743718 4345.2922948
10      MOE     PMDI         high     Softwood 4 3766.5000000 372.9025789 186.45128944 3173.1287828 4359.8712172
11      MOE     PMDI          low     Hardwood 6 3544.1666667 391.3031647 159.74884802 3133.5191797 3954.8141537
12      MOE     PMDI          low     Softwood 4 3588.5000000  48.9659746  24.48298729 3510.5842076 3666.4157924
13      MOE       UF         high     Hardwood 6 3486.3333333 406.1608877 165.81448804 3060.0936223 3912.5730444
14      MOE       UF         high     Softwood 4 3625.2500000 486.3238804 243.16194021 2851.4001818 4399.0998182
15      MOE       UF          low     Hardwood 6 3027.1666667 136.5436438  55.74370916 2883.8729004 3170.4604329
16      MOE       UF          low     Softwood 4 2907.7500000 542.3014998 271.15074989 2044.8272978 3770.6727022
17      MOR     PMDI         high     Hardwood 6   28.7333333   5.4489143   2.22450993   23.0150485   34.4516182
18      MOR     PMDI         high     Softwood 4   25.4000000   2.3593784   1.17968922   21.6457024   29.1542976
19      MOR     PMDI          low     Hardwood 6   23.0500000   4.9946972   2.03907659   17.8083868   28.2916132
20      MOR     PMDI          low     Softwood 4   21.1500000   2.6814175   1.34070877   16.8832663   25.4167337
21      MOR       UF         high     Hardwood 6   24.3500000   2.8787150   1.17523047   21.3289739   27.3710261
22      MOR       UF         high     Softwood 4   21.7250000   1.1265730   0.56328649   19.9323710   23.5176290
23      MOR       UF          low     Hardwood 6   18.6000000   3.6066605   1.47241299   14.8150419   22.3849581
24      MOR       UF          low     Softwood 4   16.3750000   2.6424421   1.32122103   12.1702850   20.5797150
=================================================================
```

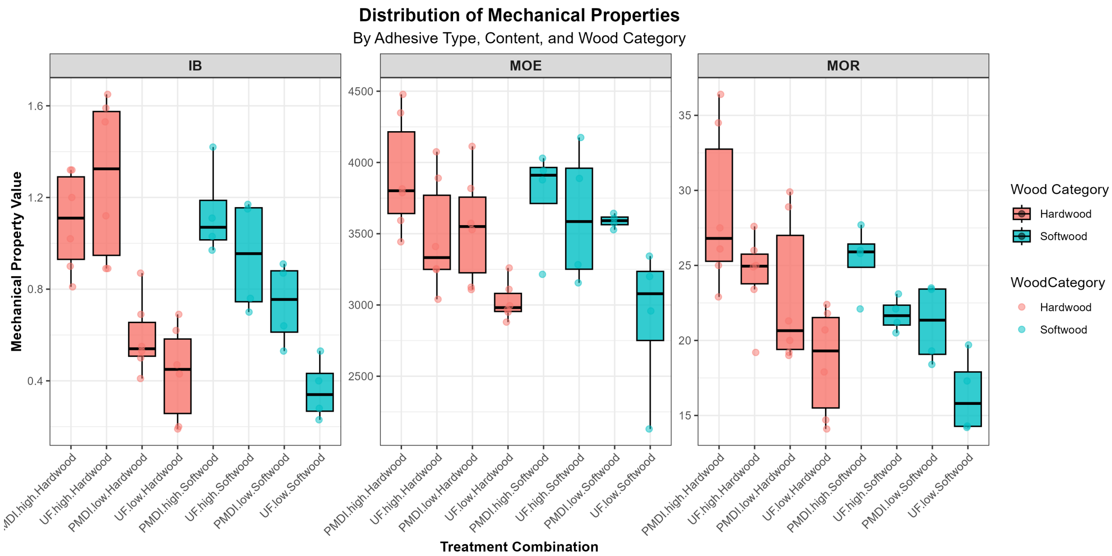
Code 5. Three way Anova results for mechanical property



(a) Normal QQ-plot



(b) Intereaction effects of resin type&content and wood type



(c) Distribution of mehcanical property

Figure 5. Three-way ANOVA for mechanical property

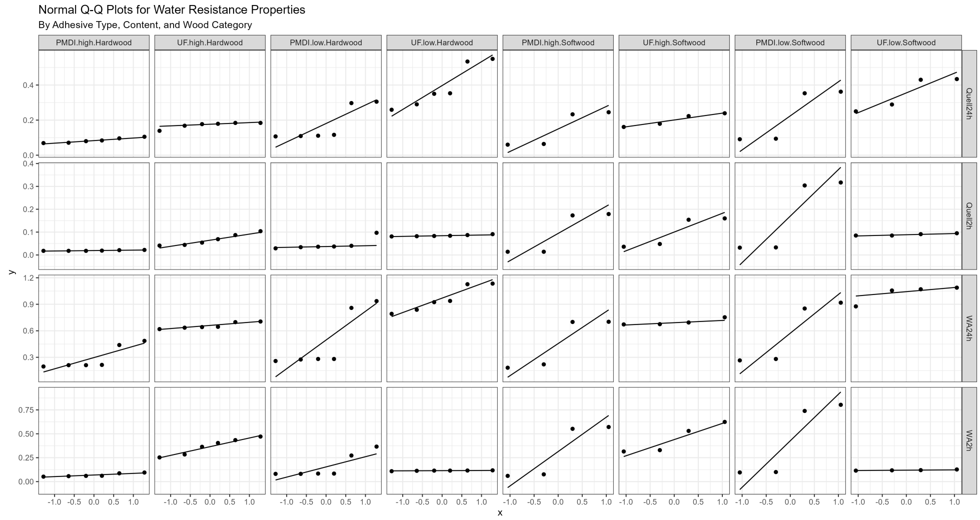
```
=================================================================
Three-way ANOVA: Effects of Resin Type, Content, and Wood Type on Water Resistance Properties
=================================================================
1. Normality Test Results (Shapiro-Wilk):
-------------------------------------------
# A tibble: 32 x 8
   LeimCode LeimgradCode WoodCategory Property variable statistic       p Normality
   <chr>    <chr>        <chr>        <chr>    <chr>        <dbl>   <dbl> <chr>
 1 PMDI     high         Hardwood     Quell24h Value        0.936 0.629   Normal
 2 PMDI     high         Softwood     Quell24h Value        0.767 0.0555  Normal
 3 PMDI     low          Hardwood     Quell24h Value        0.674 0.00327 Non-normal
 4 PMDI     low          Softwood     Quell24h Value        0.748 0.0373  Non-normal
 5 UF       high         Hardwood     Quell24h Value        0.770 0.0309  Non-normal
 6 UF       high         Softwood     Quell24h Value        0.925 0.568   Normal
 7 UF       low          Hardwood     Quell24h Value        0.855 0.174   Normal
 8 UF       low          Softwood     Quell24h Value        0.827 0.160   Normal
 9 PMDI     high         Hardwood     Quell2h  Value        0.800 0.0587  Normal
10 PMDI     high         Softwood     Quell2h  Value        0.745 0.0344  Non-normal
11 PMDI     low          Hardwood     Quell2h  Value        0.637 0.00125 Non-normal
12 PMDI     low          Softwood     Quell2h  Value        0.750 0.0389  Non-normal
13 UF       high         Hardwood     Quell2h  Value        0.924 0.532   Normal
14 UF       high         Softwood     Quell2h  Value        0.794 0.0927  Normal
15 UF       low          Hardwood     Quell2h  Value        0.905 0.405   Normal
16 UF       low          Softwood     Quell2h  Value        0.860 0.262   Normal
17 PMDI     high         Hardwood     WA24h    Value        0.717 0.00932 Non-normal
18 PMDI     high         Softwood     WA24h    Value        0.762 0.0501  Normal
19 PMDI     low          Hardwood     WA24h    Value        0.689 0.00475 Non-normal
20 PMDI     low          Softwood     WA24h    Value        0.785 0.0774  Normal
21 UF       high         Hardwood     WA24h    Value        0.854 0.170   Normal
22 UF       high         Softwood     WA24h    Value        0.815 0.133   Normal
23 UF       low          Hardwood     WA24h    Value        0.887 0.301   Normal
24 UF       low          Softwood     WA24h    Value        0.752 0.0405  Non-normal
25 PMDI     high         Hardwood     WA2h     Value        0.829 0.105   Normal
26 PMDI     high         Softwood     WA2h     Value        0.760 0.0473  Non-normal
27 PMDI     low          Hardwood     WA2h     Value        0.710 0.00783 Non-normal
28 PMDI     low          Softwood     WA2h     Value        0.771 0.0593  Normal
29 UF       high         Hardwood     WA2h     Value        0.944 0.695   Normal
30 UF       high         Softwood     WA2h     Value        0.869 0.293   Normal
31 UF       low          Hardwood     WA2h     Value        0.928 0.567   Normal
32 UF       low          Softwood     WA2h     Value        0.944 0.677   Normal
**********************************************************
2. Homogeneity of Variance Test Results (Levene's Test):
-------------------------------------------
# A tibble: 4 x 3
  Property levene_test     Homogeneity
  <chr>    <list>          <chr>
1 Quell24h <anova [2 x 3]> Non-homogeneous
2 Quell2h  <anova [2 x 3]> Non-homogeneous
3 WA24h    <anova [2 x 3]> Non-homogeneous
4 WA2h     <anova [2 x 3]> Non-homogeneous
**********************************************************
THREE-WAY ANOVA RESULTS
=================================================================

Results for Quell24h :
-------------------------------------------
Anova Table (Type III tests)

Response: Value
                                   Sum Sq Df F value  Pr(>F)
(Intercept)                      0.042504  1  5.2352 0.02889 *
LeimCode                         0.023056  1  2.8398 0.10168
LeimgradCode                     0.024300  1  2.9930 0.09326 .
WoodCategory                     0.010560  1  1.3007 0.26255
LeimCode:LeimgradCode            0.024321  1  2.9955 0.09313 .
LeimCode:WoodCategory            0.001703  1  0.2097 0.65010
LeimgradCode:WoodCategory        0.000288  1  0.0355 0.85172
LeimCode:LeimgradCode:WoodCategory 0.001597  1  0.1966 0.66043
Residuals                        0.259806 32
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Results for Quell2h :
-------------------------------------------
Anova Table (Type III tests)

Response: Value
                                   Sum Sq Df F value  Pr(>F)
(Intercept)                      0.002243  1  0.5811 0.45146
LeimCode                         0.006674  1  1.7293 0.19784
LeimgradCode                     0.002054  1  0.5322 0.47097
WoodCategory                     0.013741  1  3.5605 0.06827 .
LeimCode:LeimgradCode            0.000096  1  0.0249 0.87567
LeimCode:WoodCategory            0.002185  1  0.5660 0.45733
LeimgradCode:WoodCategory        0.003040  1  0.7877 0.38141
LeimCode:LeimgradCode:WoodCategory 0.003745  1  0.9703 0.33200
Residuals                        0.123498 32
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Results for WA24h :
------------------------------------------
Anova Table (Type III tests)

Response: Value
                                   Sum Sq Df  F value   Pr(>F)
(Intercept)                       0.51451  1 11.9305 0.001577 **
LeimCode                          0.39858  1  9.2424 0.004688 **
LeimgradCode                      0.10697  1  2.4805 0.125099
WoodCategory                      0.06004  1  1.3922 0.246728
LeimCode:LeimgradCode             0.01904  1  0.4415 0.511150
LeimCode:WoodCategory             0.01643  1  0.3809 0.541484
LeimgradCode:WoodCategory         0.00444  1  0.1030 0.750375
LeimCode:LeimgradCode:WoodCategory 0.00417  1  0.0966 0.757943
Residuals                         1.38001 32
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Results for WA2h :
------------------------------------------
Anova Table (Type III tests)

Response: Value
                                   Sum Sq Df  F value   Pr(>F)
(Intercept)                       0.02829  1  1.0219 0.319642
LeimCode                          0.26940  1  9.7315 0.003819 **
LeimgradCode                      0.02585  1  0.9339 0.341092
WoodCategory                      0.14534  1  5.2500 0.028677 *
LeimCode:LeimgradCode             0.18044  1  6.5180 0.015648 *
LeimCode:WoodCategory             0.03264  1  1.1789 0.285683
LeimgradCode:WoodCategory         0.00087  1  0.0314 0.860455
LeimCode:LeimgradCode:WoodCategory 0.00629  1  0.2273 0.636743
Residuals                         0.88586 32
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
****************************************************************
EFFECT SIZES
=================================================================
   Property                          Parameter Partial_Eta_squared      CI_low CI_high
1   Quell2h                           LeimCode        0.0085172785 0.0000000000       1
2   Quell2h                       LeimgradCode        0.0538039460 0.0000000000       1
3   Quell2h                       WoodCategory        0.2172310456 0.0433079916       1
4   Quell2h              LeimCode:LeimgradCode        0.0307680073 0.0000000000       1
5   Quell2h              LeimCode:WoodCategory        0.1159853859 0.0003725188       1
6   Quell2h          LeimgradCode:WoodCategory        0.0022755549 0.0000000000       1
7   Quell2h LeimCode:LeimgradCode:WoodCategory        0.0294289005 0.0000000000       1
8  Quell24h                           LeimCode        0.3791080775 0.1648249888       1
9  Quell24h                       LeimgradCode        0.4199556951 0.2040341188       1
10 Quell24h                       WoodCategory        0.0259551901 0.0000000000       1
11 Quell24h              LeimCode:LeimgradCode        0.0987351859 0.0000000000       1
12 Quell24h              LeimCode:WoodCategory        0.0358654987 0.0000000000       1
13 Quell24h          LeimgradCode:WoodCategory        0.0155060016 0.0000000000       1
14 Quell24h LeimCode:LeimgradCode:WoodCategory        0.0061074536 0.0000000000       1
15     WA2h                           LeimCode        0.0175672102 0.0000000000       1
16     WA2h                       LeimgradCode        0.0842884376 0.0000000000       1
17     WA2h                       WoodCategory        0.1991432876 0.0336492904       1
18     WA2h              LeimCode:LeimgradCode        0.2979567801 0.0965970245       1
19     WA2h              LeimCode:WoodCategory        0.1123324895 0.0000000000       1
20     WA2h          LeimgradCode:WoodCategory        0.0015961214 0.0000000000       1
21     WA2h LeimCode:LeimgradCode:WoodCategory        0.0070542662 0.0000000000       1
22    WA24h                           LeimCode        0.5251945320 0.3183388280       1
23    WA24h                       LeimgradCode        0.2901447365 0.0907634116       1
24    WA24h                       WoodCategory        0.0534352817 0.0000000000       1
25    WA24h              LeimCode:LeimgradCode        0.0371799258 0.0000000000       1
26    WA24h              LeimCode:WoodCategory        0.0097732259 0.0000000000       1
27    WA24h          LeimgradCode:WoodCategory        0.0006384762 0.0000000000       1
28    WA24h LeimCode:LeimgradCode:WoodCategory        0.0030102123 0.0000000000       1
**********************************************************
POST-HOC ANALYSIS RESULTS
=================================================================
Post-hoc Results for Quell24h :
------------------------------------------
# A tibble: 28 x 8
   .y.   group1             group2             estimate conf.low conf.high    p.adj p.adj.signif
 * <chr> <chr>              <chr>                 <dbl>    <dbl>     <dbl>    <dbl> <chr>
 1 Value PMDI_high_Hardwood UF_high_Hardwood    0.0877    0.0534     0.122  0.000049 ****
 2 Value PMDI_high_Hardwood PMDI_low_Hardwood   0.09     -0.0955     0.276  0.456    ns
 3 Value PMDI_high_Hardwood UF_low_Hardwood     0.305     0.0716     0.538  0.016    *
 4 Value PMDI_high_Hardwood PMDI_high_Softwood  0.0663   -0.250      0.383  0.862    ns
 5 Value PMDI_high_Hardwood UF_high_Softwood    0.116     0.0105     0.222  0.037    *
 6 Value PMDI_high_Hardwood PMDI_low_Softwood   0.141    -0.335      0.617  0.645    ns
 7 Value PMDI_high_Hardwood UF_low_Softwood     0.267    -0.0271     0.560  0.065    ns
 8 Value UF_high_Hardwood   PMDI_low_Hardwood   0.00233  -0.183      0.187  1        ns
 9 Value UF_high_Hardwood   UF_low_Hardwood     0.217    -0.0156     0.450  0.066    ns
10 Value UF_high_Hardwood   PMDI_high_Softwood -0.0213   -0.336      0.293  1        ns
11 Value UF_high_Hardwood   UF_high_Softwood    0.0287   -0.0746     0.132  0.798    ns
12 Value UF_high_Hardwood   PMDI_low_Softwood   0.0532   -0.422      0.528  0.991    ns
13 Value UF_high_Hardwood   UF_low_Softwood     0.179    -0.113      0.471  0.18     ns
14 Value PMDI_low_Hardwood  UF_low_Hardwood     0.215    -0.0292     0.459  0.095    ns
15 Value PMDI_low_Hardwood  PMDI_high_Softwood -0.0237   -0.299      0.252  1        ns
16 Value PMDI_low_Hardwood  UF_high_Softwood    0.0263   -0.157      0.209  0.998    ns
```

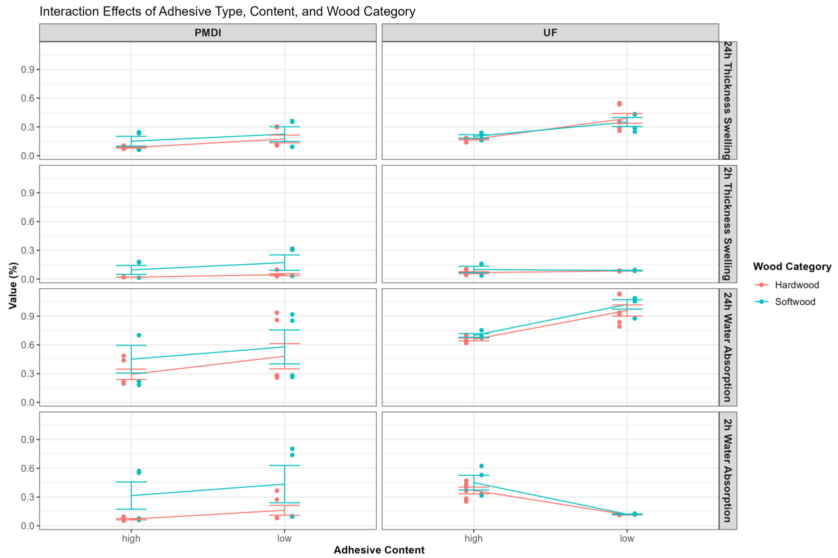
```
17 Value PMDI_low_Hardwood  PMDI_low_Softwood   0.0508   -0.364     0.466  0.997    ns
18 Value PMDI_low_Hardwood  UF_low_Softwood     0.177    -0.0825    0.436  0.226    ns
19 Value UF_low_Hardwood    PMDI_high_Softwood -0.239    -0.529     0.0513 0.119    ns
20 Value UF_low_Hardwood    UF_high_Softwood   -0.189    -0.418     0.0404 0.111    ns
21 Value UF_low_Hardwood    PMDI_low_Softwood  -0.164    -0.573     0.245  0.647    ns
22 Value UF_low_Hardwood    UF_low_Softwood    -0.0384   -0.316     0.239  0.999    ns
23 Value PMDI_high_Softwood UF_high_Softwood    0.05     -0.243     0.343  0.966    ns
24 Value PMDI_high_Softwood PMDI_low_Softwood   0.0745   -0.346     0.495  0.985    ns
25 Value PMDI_high_Softwood UF_low_Softwood     0.200    -0.103     0.503  0.232    ns
26 Value UF_high_Softwood   PMDI_low_Softwood   0.0245   -0.432     0.481  1        ns
27 Value UF_high_Softwood   UF_low_Softwood     0.150    -0.120     0.420  0.269    ns
28 Value PMDI_low_Softwood  UF_low_Softwood     0.126    -0.293     0.544  0.83     ns
*******************************************
Post-hoc Results for Quell2h :
-------------------------------------------
# A tibble: 28 x 8
   .y.   group1             group2             estimate  conf.low conf.high        p.adj p.adj.signif
 * <chr> <chr>              <chr>                 <dbl>     <dbl>     <dbl>        <dbl> <chr>
 1 Value PMDI_high_Hardwood UF_high_Hardwood    0.0472   -0.000408    0.0947 0.052        ns
 2 Value PMDI_high_Hardwood PMDI_low_Hardwood   0.0262   -0.0222      0.0745 0.353        ns
 3 Value PMDI_high_Hardwood UF_low_Hardwood     0.0653    0.0585      0.0722 0.0000000358 ****
 4 Value PMDI_high_Hardwood PMDI_high_Softwood  0.0757   -0.217       0.368  0.734        ns
 5 Value PMDI_high_Hardwood UF_high_Softwood    0.0802   -0.128       0.289  0.443        ns
 6 Value PMDI_high_Hardwood PMDI_low_Softwood   0.152    -0.350       0.655  0.622        ns
 7 Value PMDI_high_Hardwood UF_low_Softwood     0.0697    0.0554      0.0840 0.000354     ***
 8 Value UF_high_Hardwood   PMDI_low_Hardwood  -0.021    -0.0758      0.0338 0.822        ns
 9 Value UF_high_Hardwood   UF_low_Hardwood     0.0182   -0.0291      0.0655 0.666        ns
10 Value UF_high_Hardwood   PMDI_high_Softwood  0.0285   -0.252       0.309  0.996        ns
11 Value UF_high_Hardwood   UF_high_Softwood    0.033    -0.160       0.226  0.96         ns
12 Value UF_high_Hardwood   PMDI_low_Softwood   0.105    -0.390       0.600  0.859        ns
13 Value UF_high_Hardwood   UF_low_Softwood     0.0225   -0.0244      0.0694 0.486        ns
14 Value PMDI_low_Hardwood  UF_low_Hardwood     0.0392   -0.00892     0.0873 0.108        ns
15 Value PMDI_low_Hardwood  PMDI_high_Softwood  0.0495   -0.231       0.330  0.94         ns
16 Value PMDI_low_Hardwood  UF_high_Softwood    0.054    -0.139       0.247  0.762        ns
17 Value PMDI_low_Hardwood  PMDI_low_Softwood   0.126    -0.369       0.621  0.758        ns
18 Value PMDI_low_Hardwood  UF_low_Softwood     0.0435   -0.00419     0.0912 0.072        ns
19 Value UF_low_Hardwood    PMDI_high_Softwood  0.0103   -0.282       0.303  1            ns
20 Value UF_low_Hardwood    UF_high_Softwood    0.0148   -0.193       0.223  0.999        ns
21 Value UF_low_Hardwood    PMDI_low_Softwood   0.0868   -0.416       0.589  0.926        ns
22 Value UF_low_Hardwood    UF_low_Softwood     0.00433  -0.00877     0.0174 0.784        ns
23 Value PMDI_high_Softwood UF_high_Softwood    0.00450  -0.254       0.263  1            ns
24 Value PMDI_high_Softwood PMDI_low_Softwood   0.0765   -0.363       0.516  0.982        ns
25 Value PMDI_high_Softwood UF_low_Softwood    -0.00600  -0.298       0.286  1            ns
26 Value UF_high_Softwood   PMDI_low_Softwood   0.072    -0.379       0.523  0.98         ns
27 Value UF_high_Softwood   UF_low_Softwood    -0.0105   -0.218       0.197  1            ns
28 Value PMDI_low_Softwood  UF_low_Softwood    -0.0825   -0.585       0.420  0.94         ns
*******************************************
Post-hoc Results for WA24h :
-------------------------------------------
# A tibble: 28 x 8
   .y.   group1             group2             estimate conf.low conf.high    p.adj p.adj.signif
 * <chr> <chr>              <chr>                 <dbl>    <dbl>     <dbl>    <dbl> <chr>
 1 Value PMDI_high_Hardwood UF_high_Hardwood     0.364    0.118    0.611    0.008    **
 2 Value PMDI_high_Hardwood PMDI_low_Hardwood    0.189   -0.407    0.785    0.864    ns
 3 Value PMDI_high_Hardwood UF_low_Hardwood      0.666    0.367    0.965    0.000146 ***
 4 Value PMDI_high_Hardwood PMDI_high_Softwood   0.158   -0.661    0.977    0.945    ns
 5 Value PMDI_high_Hardwood UF_high_Softwood     0.406    0.160    0.651    0.004    **
 6 Value PMDI_high_Hardwood PMDI_low_Softwood    0.286   -0.744    1.32     0.763    ns
 7 Value PMDI_high_Hardwood UF_low_Softwood      0.730    0.438    1.02     0.000155 ***
 8 Value UF_high_Hardwood   PMDI_low_Hardwood   -0.176   -0.787    0.436    0.859    ns
 9 Value UF_high_Hardwood   UF_low_Hardwood      0.302    0.0335   0.570    0.03     *
10 Value UF_high_Hardwood   PMDI_high_Softwood  -0.206   -1.10     0.690    0.813    ns
11 Value UF_high_Hardwood   UF_high_Softwood     0.0412  -0.0599   0.142    0.673    ns
12 Value UF_high_Hardwood   PMDI_low_Softwood   -0.0783  -1.18     1.02     0.999    ns
13 Value UF_high_Hardwood   UF_low_Softwood      0.365    0.0776   0.653    0.024    *
14 Value PMDI_low_Hardwood  UF_low_Hardwood      0.477   -0.119    1.07     0.129    ns
15 Value PMDI_low_Hardwood  PMDI_high_Softwood  -0.0307  -0.831    0.770    1        ns
16 Value PMDI_low_Hardwood  UF_high_Softwood     0.217   -0.393    0.827    0.727    ns
17 Value PMDI_low_Hardwood  PMDI_low_Softwood    0.0973  -0.852    1.05     1        ns
18 Value PMDI_low_Hardwood  UF_low_Softwood      0.541   -0.0588   1.14     0.078    ns
19 Value UF_low_Hardwood    PMDI_high_Softwood  -0.508   -1.32     0.302    0.206    ns
20 Value UF_low_Hardwood    UF_high_Softwood    -0.260   -0.527    0.00649  0.056    ns
21 Value UF_low_Hardwood    PMDI_low_Softwood   -0.380   -1.40     0.640    0.555    ns
22 Value UF_low_Hardwood    UF_low_Softwood      0.0637  -0.240    0.367    0.985    ns
23 Value PMDI_high_Softwood UF_high_Softwood     0.248   -0.643    1.14     0.7      ns
24 Value PMDI_high_Softwood PMDI_low_Softwood    0.128   -0.877    1.13     0.998    ns
25 Value PMDI_high_Softwood UF_low_Softwood      0.572   -0.260    1.40     0.152    ns
26 Value UF_high_Softwood   PMDI_low_Softwood   -0.120   -1.22     0.978    0.992    ns
27 Value UF_high_Softwood   UF_low_Softwood      0.324    0.0443   0.604    0.031    *
28 Value PMDI_low_Softwood  UF_low_Softwood      0.444   -0.598    1.49     0.426    ns
*******************************************
Post-hoc Results for WA2h :
-------------------------------------------
# A tibble: 28 x 8
   .y.   group1             group2             estimate conf.low conf.high p.adj p.adj.signif
 * <chr> <chr>              <chr>                 <dbl>    <dbl>     <dbl> <dbl> <chr>
 1 Value PMDI_high_Hardwood UF_high_Hardwood    0.300    0.139      0.460  0.003 **
 2 Value PMDI_high_Hardwood PMDI_low_Hardwood   0.0928  -0.145      0.330  0.65  ns
 3 Value PMDI_high_Hardwood UF_low_Hardwood     0.0457   0.0122     0.0791 0.013 *
 4 Value PMDI_high_Hardwood PMDI_high_Softwood  0.246   -0.644      1.14   0.69  ns
 5 Value PMDI_high_Hardwood UF_high_Softwood    0.381   -0.0914     0.853  0.089 ns
```

```
 6 Value PMDI_high_Hardwood PMDI_low_Softwood   0.366   -0.851      1.58   0.629 ns
 7 Value PMDI_high_Hardwood UF_low_Softwood     0.0513   0.0184     0.0843 0.006 **
 8 Value UF_high_Hardwood   PMDI_low_Hardwood  -0.207   -0.447      0.0330 0.103 ns
 9 Value UF_high_Hardwood   UF_low_Hardwood    -0.254   -0.416     -0.0916 0.008 **
10 Value UF_high_Hardwood   PMDI_high_Softwood -0.0536  -0.901      0.794  1     ns
11 Value UF_high_Hardwood   UF_high_Softwood    0.0812  -0.338      0.501  0.959 ns
12 Value UF_high_Hardwood   PMDI_low_Softwood   0.0662  -1.12       1.25   1     ns
13 Value UF_high_Hardwood   UF_low_Softwood    -0.248   -0.410     -0.0862 0.008 **
14 Value PMDI_low_Hardwood  UF_low_Hardwood    -0.0472  -0.286      0.192  0.97  ns
15 Value PMDI_low_Hardwood  PMDI_high_Softwood  0.153   -0.658      0.965  0.948 ns
16 Value PMDI_low_Hardwood  UF_high_Softwood    0.288   -0.119      0.695  0.181 ns
17 Value PMDI_low_Hardwood  PMDI_low_Softwood   0.273   -0.876      1.42   0.839 ns
18 Value PMDI_low_Hardwood  UF_low_Softwood    -0.0415  -0.280      0.197  0.985 ns
19 Value UF_low_Hardwood    PMDI_high_Softwood  0.200   -0.692      1.09   0.818 ns
20 Value UF_low_Hardwood    UF_high_Softwood    0.335   -0.141      0.812  0.125 ns
21 Value UF_low_Hardwood    PMDI_low_Softwood   0.320   -0.899      1.54   0.723 ns
22 Value UF_low_Hardwood    UF_low_Softwood     0.00567 -0.00826    0.0196 0.561 ns
23 Value PMDI_high_Softwood UF_high_Softwood    0.135   -0.648      0.918  0.981 ns
24 Value PMDI_high_Softwood PMDI_low_Softwood   0.120   -0.960      1.20   0.999 ns
25 Value PMDI_high_Softwood UF_low_Softwood    -0.195   -1.09       0.697  0.833 ns
26 Value UF_high_Softwood   PMDI_low_Softwood  -0.0150  -1.12       1.09   1     ns
27 Value UF_high_Softwood   UF_low_Softwood    -0.330   -0.805      0.146  0.13  ns
28 Value PMDI_low_Softwood  UF_low_Softwood    -0.314   -1.53       0.904  0.735 ns

DESCRIPTIVE STATISTICS
============================================================
# A tibble: 32 x 10
   Property LeimCode LeimgradCode WoodCategory     n   mean      sd       se ci_lower ci_upper
   <chr>    <chr>    <chr>        <chr>        <int>  <dbl>   <dbl>    <dbl>    <dbl>    <dbl>
 1 Quell24h PMDI     high         Hardwood         6 0.0842 0.0141  0.00576   0.0694   0.0990
 2 Quell24h PMDI     high         Softwood         4 0.150  0.102   0.0512   -0.0123   0.313
 3 Quell24h PMDI     low          Hardwood         6 0.174  0.0983  0.0401    0.0710   0.277
 4 Quell24h PMDI     low          Softwood         4 0.225  0.153   0.0765   -0.0185   0.469
 5 Quell24h UF       high         Hardwood         6 0.172  0.0171  0.00699   0.154    0.190
 6 Quell24h UF       high         Softwood         4 0.200  0.0366  0.0183    0.142    0.259
 7 Quell24h UF       low          Hardwood         6 0.389  0.123   0.0504    0.260    0.519
 8 Quell24h UF       low          Softwood         4 0.351  0.0952  0.0476    0.199    0.502
 9 Quell2h  PMDI     high         Hardwood         6 0.0193 0.00175 0.000715  0.0175   0.0212
10 Quell2h  PMDI     high         Softwood         4 0.095  0.0936  0.0468   -0.0539   0.244
11 Quell2h  PMDI     low          Hardwood         6 0.0455 0.0255  0.0104    0.0187   0.0723
12 Quell2h  PMDI     low          Softwood         4 0.172  0.161   0.0803   -0.0840   0.427
13 Quell2h  UF       high         Hardwood         6 0.0665 0.0251  0.0102    0.0402   0.0928
14 Quell2h  UF       high         Softwood         4 0.0995 0.0666  0.0333   -0.00651  0.206
15 Quell2h  UF       low          Hardwood         6 0.0847 0.00372 0.00152   0.0808   0.0886
16 Quell2h  UF       low          Softwood         4 0.089  0.00490 0.00245   0.0812   0.0968
17 WA24h    PMDI     high         Hardwood         6 0.293  0.132   0.0541    0.154    0.432
18 WA24h    PMDI     high         Softwood         4 0.451  0.289   0.145    -0.00901  0.911
19 WA24h    PMDI     low          Hardwood         6 0.482  0.323   0.132     0.143    0.821
20 WA24h    PMDI     low          Softwood         4 0.579  0.354   0.177     0.0150   1.14
21 WA24h    UF       high         Hardwood         6 0.657  0.0354  0.0145    0.620    0.695
22 WA24h    UF       high         Softwood         4 0.698  0.0376  0.0188    0.639    0.758
23 WA24h    UF       low          Hardwood         6 0.959  0.144   0.0586    0.808    1.11
24 WA24h    UF       low          Softwood         4 1.02   0.0985  0.0493    0.866    1.18
25 WA2h     PMDI     high         Hardwood         6 0.0687 0.0178  0.00725   0.0500   0.0873
26 WA2h     PMDI     high         Softwood         4 0.315  0.285   0.143    -0.139    0.768
27 WA2h     PMDI     low          Hardwood         6 0.162  0.126   0.0514    0.0294   0.294
28 WA2h     PMDI     low          Softwood         4 0.434  0.389   0.195    -0.185    1.05
29 WA2h     UF       high         Hardwood         6 0.368  0.0855  0.0349    0.279    0.458
30 WA2h     UF       high         Softwood         4 0.450  0.152   0.0761    0.207    0.692
31 WA2h     UF       low          Hardwood         6 0.114  0.00308 0.00126   0.111    0.118
32 WA2h     UF       low          Softwood         4 0.12   0.00510 0.00255   0.112    0.128
============================================================
```

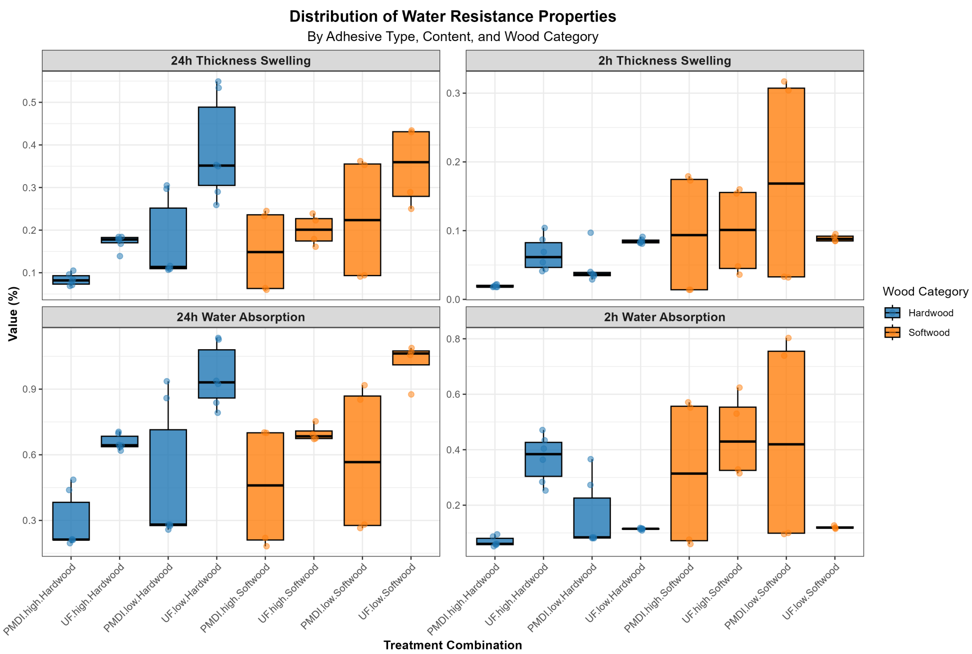
Code 6. Three way Anova results for water resistent property



(a) Normal QQ-plot



(b) Intereaction effects of resin type&content and wood type



(c) Distribution of water resistant property

Figure 6. Three-way ANOVA for water resistant property

5. Melamine-Based Primer treatment

5.1. UF-Bonded Particleboard Performance with treatment

Urea-formaldehyde (UF) resin is widely used in particleboard production due to its low cost and good bonding performance in dry conditions. However, statistical analysis in Sections 4.1 and 4.5 indicates that its moisture resistance is insufficient. To improve the water resistance of UF-based particleboard, pretreatment processes need to be considered. Therefore, this study conducts a multiple linear regression (MLR) analysis on UF particleboard treated with a melamine-based pretreatment to assess whether this approach can compensate for the inherent drawbacks of UF adhesives.

•**MLR Model Assessment**

The MLR analysis reveals that manufacturing parameters (wood density, resin coating, and urea-formaldehyde resin dosage) impact the water resistance of particleboards, with a notable time-dependent effect. Model predictive capabilities increase with extended testing time, with the WA24h model performing best (R^2=0.782, adjusted R^2=0.764, F=43.01, p<0.001), followed by Quell24h (R^2=0.666, adjusted R^2=0.639, F=23.96, p<0.001). Short-term indicator models show relatively weaker predictive power (WA2h: R^2=0.452, adjusted R^2=0.406, F=9.894, p<0.001; Quell2h: R^2=0.189, adjusted R^2=0.121, F=2.794, p=0.054). These results are further validated in prediction plots, the prediction points for the 24-hour test indicators align more closely with the ideal prediction line (diagonal), and their confidence intervals (gray bands) are narrower. Among them, WA24h exhibits the best predictive performance ($R^2 = 0.844$), followed by Quell24h ($R^2 = 0.764$). In contrast, the prediction points for the 2-hour test indicators are more scattered, particularly for Quell2h ($R^2 = 0.295$), which shows a larger prediction bias. All predictor variables have low variance inflation factors (VIF) (Dens_mitt:1.257779, LeimgradCode:1.002103, Primer:1.255677), indicating minimal multicollinearity and reliable regression coefficient estimates.

•**Wood dentisty**(wood tyep and spieces depends)

Wood density exhibits a significant negative correlation with long-term water absorption (WA24h: β= -0.0023688, t= -3.600, p= 0.000952), meaning that higher density corresponds to lower 24-hour water absorption. However, this relationship is weaker in the 2-hour immersion test (Quell2h: β= -9.868e-05,t = -0.313, p= 0.756; WA2h: β= -0.0003763, t= -0.591, p= 0.558), suggesting that the influence of density on water resistance is a gradual process that strengthens over time. Interaction plots **??**indicate that the strength of this density effect varies depending on resin content and primer treatment conditions.

•**Effect of Resin Content**

The influence of resin content (LeimgradCode) is observed in both short- and long-term tests, with the most pronounced effect in long-term testing. The low-resin-content group demonstrates better water resistance compared to the high-resin-content group (WA24h: β= 0.2286539, t= 6.860, p< 0.001; Quell24h: β= 0.1263586, t = 5.474, p < 0.001). Although this effect is also present in short-term tests, its strength is weaker (Quell2h: β= 0.03952, t = 2.478, p = 0.018; WA2h: β = -0.1341730, t = -4.160, p < 0.001). This finding suggests that increasing resin content does not necessarily improve water resistance, and an optimal ratio must be identified during production.

•**Effect of Primer Coating**

The effect of primer coating on water resistance becomes more pronounced over time. In the 24-hour tests, the non-primed group exhibits higher water absorption and thickness swelling rates compared to the primed group (WA24h: β= 0.2111428, t = 5.659, p < 0.001; Quell24h: β= 0.1278034, t = 4.946, p < 0.001). In short-term tests, the primer effect remains significant for water absorption (WA2h: β= 0.1029728, t = 2.852, p = 0.007) but is not significant for thickness swelling (Quell2h: β= 0.02033, t = 1.139, p = 0.262). This not only demonstrates the primer coating's critical role in long-term water resistance but also reveals that its water-resistance mechanism likely focuses more on preventing water penetration.

Among the three factors, urea-formaldehyde resin content showed the most significant influence on the water resistance of particleboard, demonstrated by the highest regression coefficients and t-values (WA24h: $\beta = 0.2286539$, $t = 6.860$, $p < 0.001$; Quell24h: $\beta = 0.1263586$, $t = 5.474$, $p < 0.001$), with its impact equally evident in short-term testing (WA2h: $\beta = -0.1341730$, $t = -4.160$, $p < 0.001$). The influence of resin coating ranked second, showing consistent significance in long-term tests (WA24h: $\beta = 0.2111428$, $t = 5.659$, $p < 0.001$; Quell24h: $\beta = 0.1278034$, $t = 4.946$, $p < 0.001$). Wood density had the least impact, reaching significance only in long-term water absorption tests (WA24h: $\beta = -0.0023688$, $t = -3.600$, $p < 0.001$). This indicates that while resin coating can enhance water resistance, priority should be given to optimizing resin content.

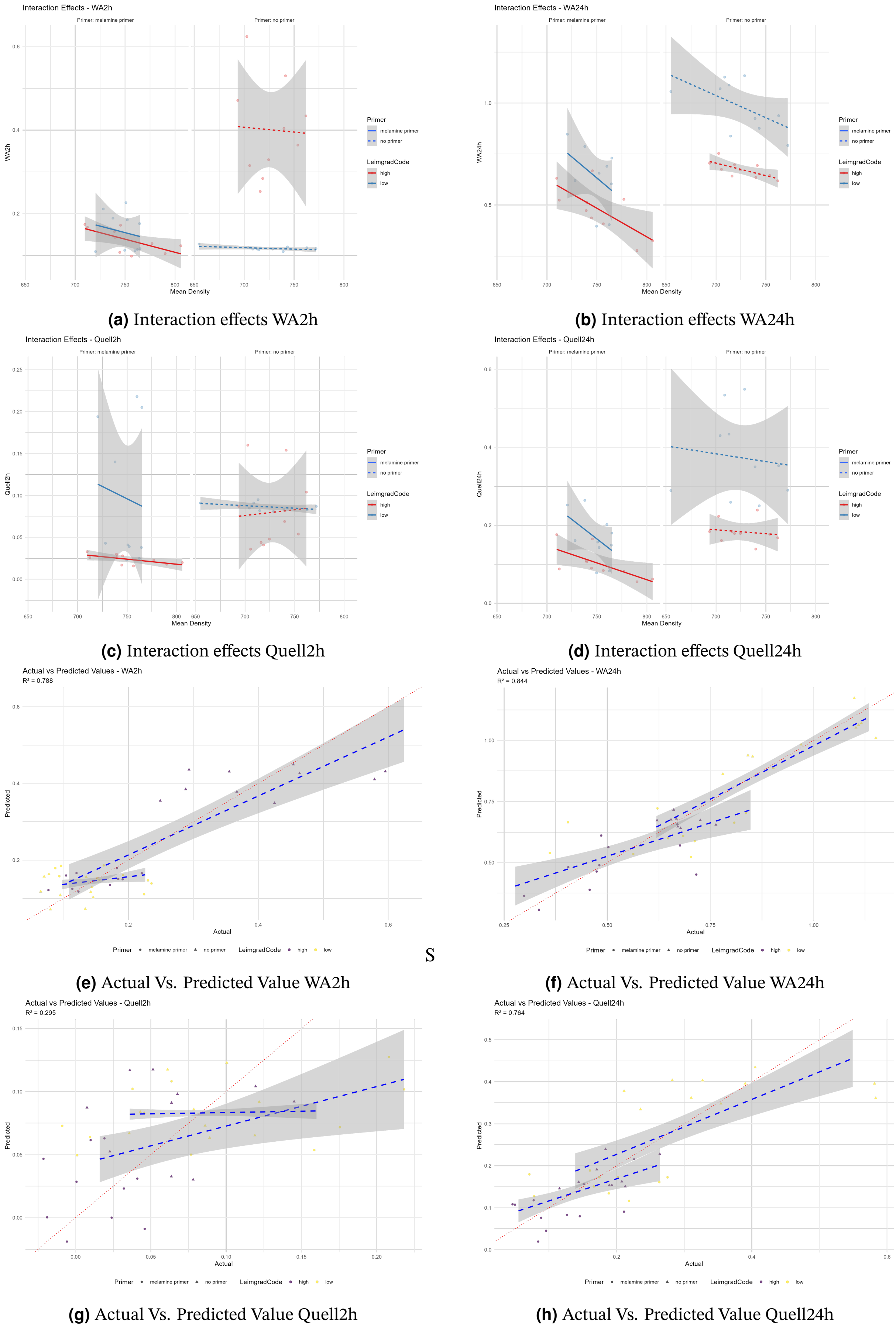
5.2. MLR analysis results for treated UF-Bonded Particleboard

```
**********************************
Treated UF-Bonded Particleboard
REGRESSION ANALYSIS SUMMARY (MLR)
==================================
[1] "The coorelation matrix"
           Dens_mitt    Dens_max   Dens_min     Quell2h    Quell24h         WA2h       WA24h
Dens_mitt  1.0000000  0.401127811  0.8358589 -0.15433722 -0.41450228 -0.238571328 -0.55869251
Dens_max   0.4011278  1.000000000  0.3551250  0.01705121 -0.06782529  0.008844648 -0.19776725
Dens_min   0.8358589  0.355124986  1.0000000 -0.12921959 -0.46176528 -0.162774747 -0.57007910
Quell2h   -0.1543372  0.017051212 -0.1292196  1.00000000  0.42563062  0.192420786  0.49576707
Quell24h  -0.4145023 -0.067825291 -0.4617653  0.42563062  1.00000000 -0.119876714  0.94182187
WA2h      -0.2385713  0.008844648 -0.1627747  0.19242079 -0.11987671  1.000000000 -0.05657305
WA24h     -0.5586925 -0.197767248 -0.5700791  0.49576707  0.94182187 -0.056573054  1.00000000
*******************************************************************************************
Results for Quell2h
----------------
```

```
Call:
lm(formula = formula, data = data)

Residuals:
      Min        1Q    Median        3Q       Max
-0.057053 -0.022099 -0.015666 -0.008348  0.138967

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)      1.145e-01  2.371e-01   0.483    0.632
Dens_mitt       -9.868e-05  3.148e-04  -0.313    0.756
LeimgradCodelow  3.952e-02  1.595e-02   2.478    0.018 *
Primerno primer  2.033e-02  1.785e-02   1.139    0.262
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.05038 on 36 degrees of freedom
Multiple R-squared:  0.1888,  Adjusted R-squared:  0.1213
F-statistic: 2.794 on 3 and 36 DF,  p-value: 0.05415

Performance Metrics:
RMSE: 0.04779231
MAE: 0.03471348

Standardized Coefficients:
    (Intercept)       Dens_mitt LeimgradCodelow Primerno primer
    682.9453351      -0.5885528     235.7017572     121.2181992
--------------------------------
Results for Quell24h
--------------------------------
Call:
lm(formula = formula, data = data)

Residuals:
      Min        1Q    Median        3Q       Max
-0.120079 -0.043081 -0.007179  0.031530  0.209650

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)      0.5536183  0.3431589   1.613    0.115
Dens_mitt       -0.0006428  0.0004557  -1.411    0.167
LeimgradCodelow  0.1263586  0.0230823   5.474 3.51e-06 ***
Primerno primer  0.1278034  0.0258382   4.946 1.77e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.07292 on 36 degrees of freedom
Multiple R-squared:  0.6663,  Adjusted R-squared:  0.6385
F-statistic: 23.96 on 3 and 36 DF,  p-value: 1.066e-08

Performance Metrics:
RMSE: 0.06917433
MAE: 0.05326584

Standardized Coefficients:
    (Intercept)       Dens_mitt LeimgradCodelow Primerno primer
    1463.215061       -1.698971      333.966089      337.784778
--------------------------------
Results for WA2h
--------------------------------
Call:
lm(formula = formula, data = data)

Residuals:
     Min       1Q   Median       3Q      Max
-0.11298 -0.07547 -0.04937  0.05775  0.28984

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)      0.4956217  0.4794849   1.034 0.308192
Dens_mitt       -0.0003763  0.0006367  -0.591 0.558246
LeimgradCodelow -0.1341730  0.0322522  -4.160 0.000188 ***
Primerno primer  0.1029728  0.0361029   2.852 0.007149 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1019 on 36 degrees of freedom
Multiple R-squared:  0.4519,  Adjusted R-squared:  0.4062
F-statistic: 9.894 on 3 and 36 DF,  p-value: 6.749e-05

Performance Metrics:
RMSE: 0.09665507
MAE: 0.08224603

Standardized Coefficients:
    (Intercept)       Dens_mitt LeimgradCodelow Primerno primer
   1201.4260029      -0.9121341    -325.2460083     249.6141721
--------------------------------
Results for WA24h
--------------------------------
Call:
```

```
lm(formula = formula, data = data)

Residuals:
     Min       1Q   Median       3Q      Max
-0.27784 -0.04398 -0.01060  0.07913  0.21290

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)      2.2210187  0.4955385   4.482 7.23e-05 ***
Dens_mitt       -0.0023688  0.0006581  -3.600 0.000952 ***
LeimgradCodelow  0.2286539  0.0333320   6.860 5.02e-08 ***
Primerno primer  0.2111428  0.0373117   5.659 1.99e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1053 on 36 degrees of freedom
Multiple R-squared:  0.7818,  Adjusted R-squared:  0.7637
F-statistic: 43.01 on 3 and 36 DF,  p-value: 5.452e-12

Performance Metrics:
RMSE: 0.09989117
MAE: 0.0744906

Standardized Coefficients:
    (Intercept)       Dens_mitt LeimgradCodelow Primerno primer
    3286.648176       -3.505396      338.360448      312.447630
```

Code 7. Treated UF-Bonded Particleboard MLR results



(a) Interaction effects WA2h

(b) Interaction effects WA24h

(c) Interaction effects Quell2h

(d) Interaction effects Quell24h

(e) Actual Vs. Predicted Value WA2h

(f) Actual Vs. Predicted Value WA24h

(g) Actual Vs. Predicted Value Quell2h

(h) Actual Vs. Predicted Value Quell24h

Figure 7. Treated UF-Bonded Particleboard MLR analysis

5.3. PMDI-Bonded Particleboard Performance with treatment

In this section, MLR analysis of the effects of wood average density, PMDI content, and primer treatment on material water resistance showed that among the four models, the Quell24h model demonstrated the best explanatory power ($R^2 = 0.276$), with both primer treatment ($p = 0.00828$) and PMDI content ($p = 0.0394$) being significant, having standardized coefficients of 256.94 and 204.06 respectively. The Quell2h model ($R^2 = 0.169$) showed significance only in primer treatment ($p = 0.0193$), with a standardized coefficient of 241.24. The WA2h&WA24h models showed weaker explanatory power ($R^2 \leq 0.142$) with no significant variables, with the WA24h model showing the largest prediction error ($RMSE = 0.244$). From the R^2 values, all models showed relatively low explanatory power.

Regarding data distribution, the Quell2h&Quell24h thickness swelling test values were relatively concentrated, with Quell2h values mainly distributed in the 0.02-0.08mm range, with occasional outliers reaching 0.3mm; Quell24h values were distributed in the 0.05-0.15mm range. In contrast, the WA series showed a wider range of water absorption values, with WA2h values distributed in the 0.05-0.4 range, and WA24h values extending to the 0.2-0.8 range. Box plots clearly showed more outliers when LeimgradCode was low, particularly in Quell2h and Quell24h, where outliers reached up to 0.3 and 0.35.

Interaction effect analysis showed that density factor was non-significant in all models (Quell2h: $p = 0.6970$, Quell24h: $p = 0.82569$, WA2h: $p = 0.8208$, WA24h: $p = 0.438$), with trend lines nearly horizontal. Primer treatment showed significance in the Quell series, reaching significant levels in both Quell2h ($p = 0.0193$) and Quell24h ($p = 0.00828$), with the no-primer group generally showing thickness swelling values 0.05-0.1mm higher than the primer group. PMDI content was only significant in Quell24h ($p = 0.0394$), with the Low group showing thickness swelling values approximately 0.05mm higher than the High group.

Regarding prediction errors, RMSE values increased with test duration: 0.065 for Quell2h, increasing to 0.072 for Quell24h, reaching 0.173 for WA2h, and 0.244 for WA24h. The actual vs. predicted value plots showed that predicted values had a notably smaller range than actual observed values, such as in WA24h where actual values ranged from 0.25-0.75 while predictions only ranged from 0.25-0.55. Different treatment groups showed clear clustering in predicted values, particularly in the no-primer-low PMDI content group (predictions concentrated at 0.15-0.20) and primer-high PMDI content group (predictions concentrated at 0.05-0.10).

While the study identified primer treatment as the most crucial factor through significance testing (Quell2h: $p = 0.0193$; Quell24h: $p = 0.00828$), the models showed overall low explanatory power ($R^2 < 0.3$) with decreasing predictive ability over test duration (RMSE increasing from 0.065 to 0.244). Particularly in water absorption tests, data variability was higher, as evidenced by larger prediction errors in the WA series tests (RMSE: 0.173-0.244).

Based on regression analysis results and data distribution characteristics, the current models' insufficient predictive capability may be attributed to:

first, consistently low model explanatory power, with even the best-performing Quell24h model having an R^2 value of only 0.276, indicating that the three factors considered (density, PMDI content, and primer treatment) explain only 27.6% of variation, dropping to 0.112 in the WA24h model, suggesting numerous unincorporated influential factors.

Second, significant data variability, particularly evident in box plots for low LeimgradCode groups showing numerous outliers, with variability increasing over test duration, such as WA24h test values ranging from 0.2 to 0.8, directly affecting model prediction stability.

Third, the current linear regression models may inadequately capture potential non-linear relationships in the data, evidenced by non-linear trends in interaction effect plots.

Finally, the relatively limited sample size for each treatment combination, as shown in scatter plots, may prevent samples from fully representing the population, affecting model estimation reliability. These issues suggest cautious use of prediction results in practical applications while indicating directions for future research improvements.

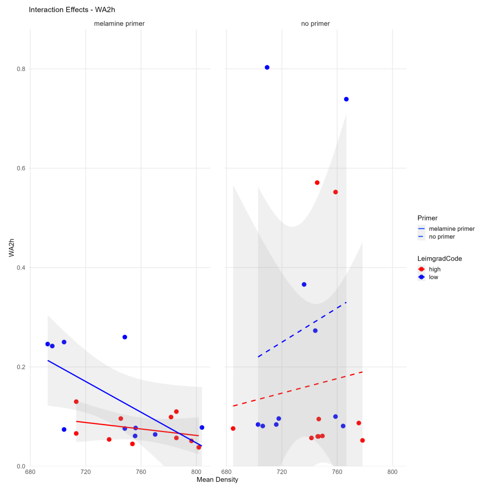
5.4. MLR analysis results for treated PMDI-Bonded Particleboard

```
**********************************
Treated UF-Bonded Particleboard
REGRESSION ANALYSIS SUMMARY (MLR)
==================================
[1] "The correlation matrix"
            Dens_mitt  Dens_max   Dens_min      Quell2h    Quell24h        WA2h       WA24h
Dens_mitt   1.00000000 0.6200312  0.8356110 -0.03296136 -0.1622188 -0.1238091 -0.1874169
Dens_max    0.62003122 1.0000000  0.2739811  0.28981816  0.2974545  0.2787219  0.2911840
Dens_min    0.83561096 0.2739811  1.0000000 -0.19898811 -0.3669898 -0.2844360 -0.4147177
Quell2h    -0.03296136 0.2898182 -0.1989881  1.00000000  0.8480259  0.9528322  0.6269763
Quell24h   -0.16221883 0.2974545 -0.3669898  0.84802587  1.0000000  0.9163404  0.8726643
WA2h       -0.12380914 0.2787219 -0.2844360  0.95283219  0.9163404  1.0000000  0.7813889
WA24h      -0.18741687 0.2911840 -0.4147177  0.62697632  0.8726643  0.7813889  1.0000000
**********************************************************************************************
Results for Quell2h
----------------
Call:
lm(formula = formula, data = data)

Residuals:
      Min        1Q    Median        3Q       Max
-0.057488 -0.042712 -0.015795  0.006931  0.226370

```

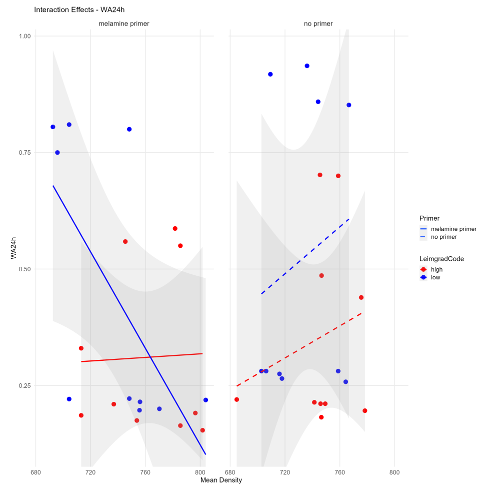
```
Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)     -0.1032689  0.2833417  -0.364   0.7176
Dens_mitt        0.0001461  0.0003723   0.393   0.6970
LeimgradCodelow  0.0279107  0.0228561   1.221   0.2300
Primerno primer  0.0539481  0.0220167   2.450   0.0193 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.06864 on 36 degrees of freedom
Multiple R-squared:  0.1694,  Adjusted R-squared:  0.1002
F-statistic: 2.447 on 3 and 36 DF,  p-value: 0.07954


Performance Metrics:
RMSE: 0.06511635
MAE: 0.04275077

Standardized Coefficients:
    (Intercept)       Dens_mitt LeimgradCodelow Primerno primer
   -461.7929293       0.6535459     124.8094862     241.2422128

Results for Quell24h
----------------
Call:
lm(formula = formula, data = data)

Residuals:
     Min       1Q   Median       3Q      Max
-0.09073 -0.05449 -0.02038  0.05010  0.18474

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)      1.250e-01  3.145e-01   0.398  0.69333
Dens_mitt       -9.168e-05  4.133e-04  -0.222  0.82569
LeimgradCodelow  5.424e-02  2.537e-02   2.138  0.03937 *
Primerno primer  6.829e-02  2.444e-02   2.795  0.00828 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.07618 on 36 degrees of freedom
Multiple R-squared:  0.2757,  Adjusted R-squared:  0.2154
F-statistic: 4.568 on 3 and 36 DF,  p-value: 0.008223


Performance Metrics:
RMSE: 0.07227102
MAE: 0.06055134

Standardized Coefficients:
    (Intercept)       Dens_mitt LeimgradCodelow Primerno primer
    470.3287311      -0.3449241     204.0582652     256.9371309

Results for WA2h
----------------
Call:
lm(formula = formula, data = data)

Residuals:
     Min       1Q   Median       3Q      Max
-0.18623 -0.11536 -0.04062  0.05109  0.53647

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)      0.2366578  0.7506983   0.315   0.7544
Dens_mitt       -0.0002251  0.0009865  -0.228   0.8208
LeimgradCodelow  0.0815712  0.0605561   1.347   0.1864
Primerno primer  0.1079698  0.0583322   1.851   0.0724 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1819 on 36 degrees of freedom
Multiple R-squared:  0.1419,  Adjusted R-squared:  0.07044
F-statistic: 1.985 on 3 and 36 DF,  p-value: 0.1336


Performance Metrics:
RMSE: 0.1725222
MAE: 0.1224016

Standardized Coefficients:
    (Intercept)       Dens_mitt LeimgradCodelow Primerno primer
    405.9777716      -0.3861361     139.9324148     185.2182564

Results for WA24h
----------------
Call:
lm(formula = formula, data = data)

Residuals:
    Min      1Q  Median      3Q     Max
```

```
-0.2698 -0.2153 -0.1255  0.2823  0.4297

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)       1.134895   1.063432   1.067    0.293
Dens_mitt        -0.001096   0.001397  -0.784    0.438
LeimgradCodelow   0.127824   0.085783   1.490    0.145
Primerno primer   0.050242   0.082633   0.608    0.547

Residual standard error: 0.2576 on 36 degrees of freedom
Multiple R-squared:  0.1115,  Adjusted R-squared:  0.03747
F-statistic: 1.506 on 3 and 36 DF,  p-value: 0.2295

Performance Metrics:
RMSE: 0.2443932
MAE: 0.2254824

Standardized Coefficients:
    (Intercept)       Dens_mitt LeimgradCodelow Primerno primer
    1398.496005       -1.350441      157.514075       61.911467
```

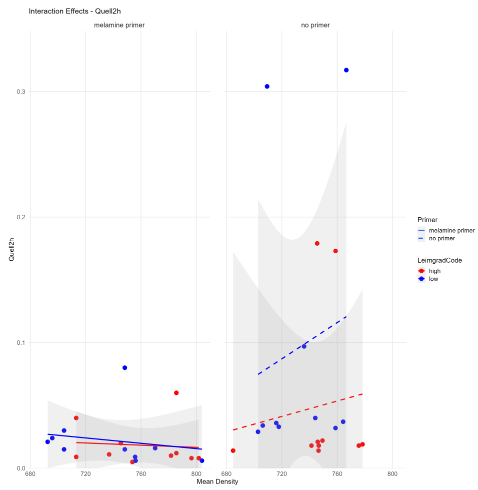
Code 8. Treated PMDI-Bonded Particleboard MLR results



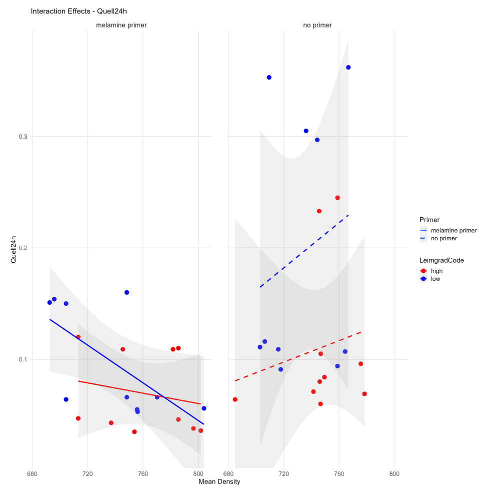
(a) Interaction effects WA2h



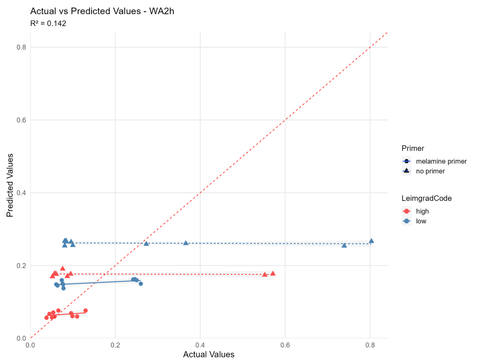
(b) Interaction effects WA24h



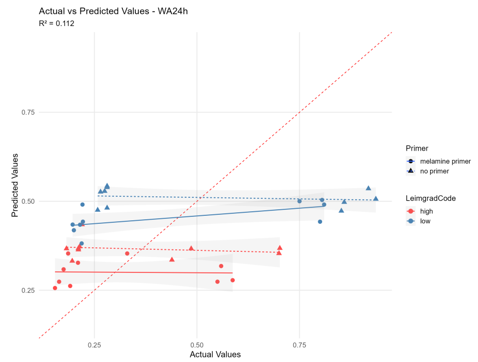
(c) Interaction effects Quell2h



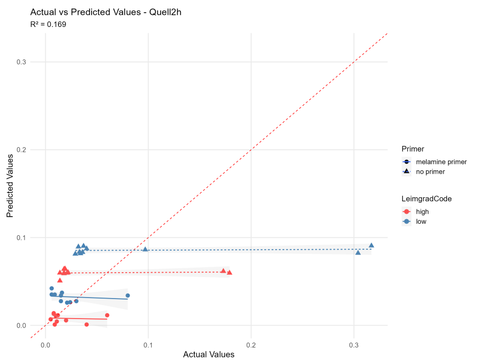
(d) Interaction effects Quell24h



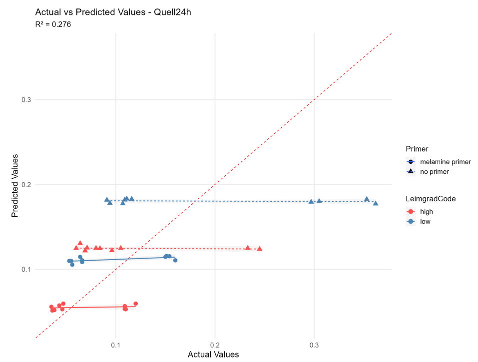
(e) Actual Vs. Predicted Value WA2h



(f) Actual Vs. Predicted Value WA24h

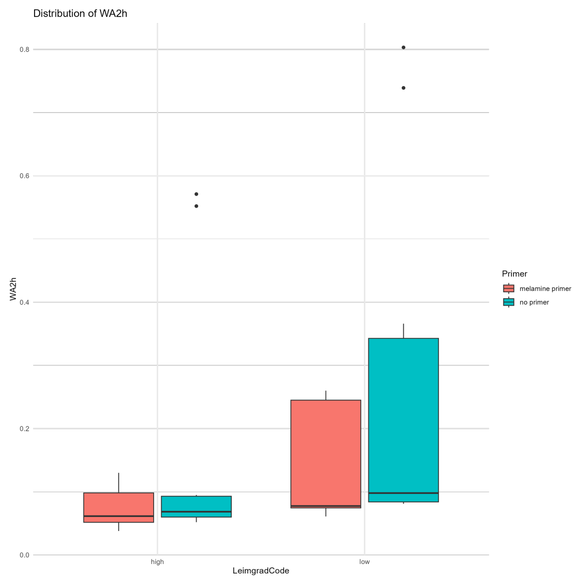


(g) Actual Vs. Predicted Value Quell2h

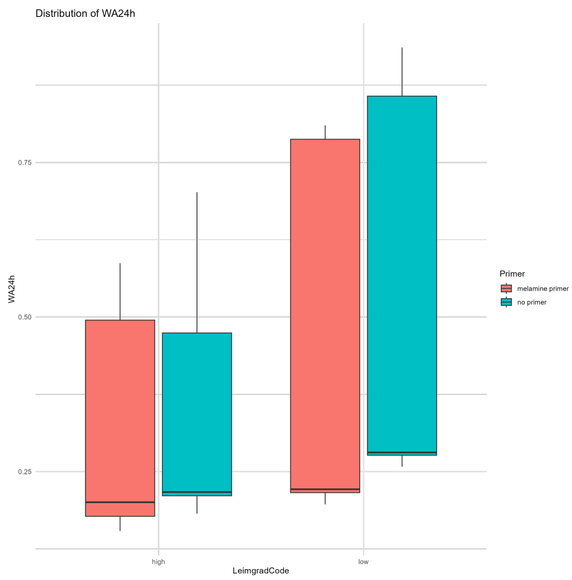


(h) Actual Vs. Predicted Value Quell24h

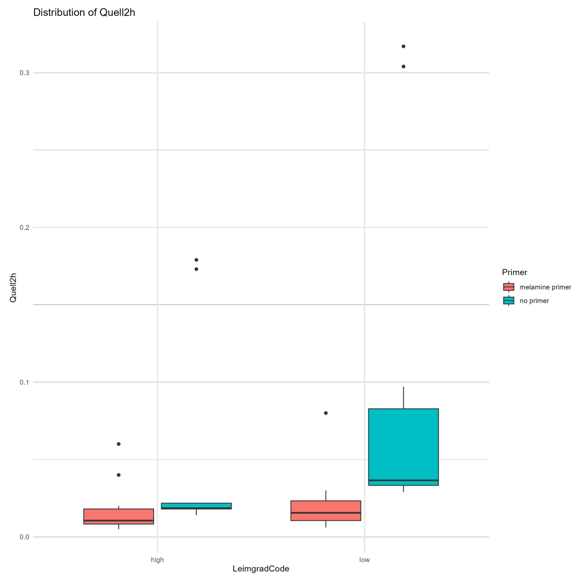
Figure 8. Treated PMDI-Bonded Particleboard MLR analysis



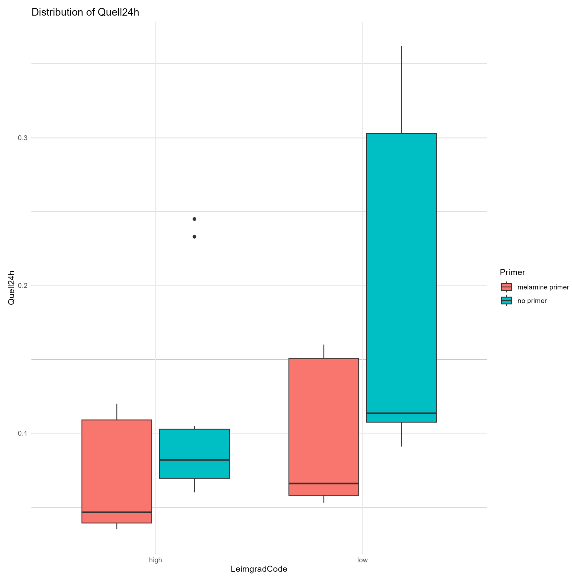
(a) Box plot WA2h



(b) Box plot WA24h



(c) Box plot Quell2h



(d) Box plot Quell24h

Figure 9. WA2h&24h and Quell2h&24h Boxplot of PMDI(2/4%)-Bonded Particleboard

6. Conclusion

•Feasibility of Hardwood as Alternative Material for Particleboard

Research results indicate that hardwood is a technically viable alternative in particleboard production. Particularly when using PMDI resin, hardwood particleboards demonstrate mechanical properties comparable to traditional softwood particleboards, with certain advantages in short-term water resistance.

•Optimal Resin Type and Content

PMDI resin at 4% content level demonstrates optimal overall performance: internal bond strength ($\eta^2 = 0.64$, $p < 0.001$), bending strength (MOR $\eta^2 = 0.295$, $p = 0.0197$), and water resistance (WA24h test $\eta^2 = 0.53$) all superior to other formulations. While UF resin at 12% content shows good mechanical properties (IB: $\eta^2 = 0.717$; MOR: $\eta^2 = 0.544$), it exhibits notable deficiencies in water resistance in section 4. However, melamine primer treatment can significantly improve its water resistance, making it advantageous in specific applications.

•Effectiveness of Melamine Primer Treatment

Multiple linear regression analysis of melamine primer treatment shows impact on improving board water resistance, particularly for UF-bonded boards. The treatment demonstrates stronger effects in long-term water exposure tests (WA24h: $R^2 = 0.782$) compared to short-term tests (WA2h: $R^2 = 0.452$), indicating sustained moisture protection.

However, treatment effectiveness varies with resin type and wood species. UF-bonded boards show more significant improvement from coating treatment compared to PMDI-bonded boards, suggesting the treatment's value in enhancing the performance of more economical UF-based products.

•**Water Resistance of Hardwood and Softwood Particleboard**

The water resistance of Hardwood and softwood Particleboard exhibits distinct time-dependent characteristics. Hardwood shows significant advantages in short-term water resistance, particularly when bonded with PMDI resin, with notably lower 2-hour water absorption than softwood. However, this advantage gradually weakens under long-term immersion conditions (24-hour test), and the water resistance of the two woods tends to approach.

This result indicates that relying solely on wood's physical properties for long-term water protection is insufficient. Therefore, to achieve ideal water resistance, it is recommended to use PMDI resin systems combined with melamine primer surface treatment, while selecting appropriate wood types based on specific application requirements.

•**Manufacturing Process Implications**

Analysis results from Section 5.2 reveal a significant negative correlation between density and long-term water absorption, though this relationship varies with resin type and content.

This indicates the need for precise balance between density control and resin application in particleboard production. Additionally, observed variations in melamine treatment effectiveness across different wood-resin combinations suggest the need for customized treatment parameters and manufacturing solutions for different wood-resin combinations systems, rather than adopting unified manufacturing standards.

•**Limitations and Future Research Directions**

The study has two main limitations : first, the relatively low R^2 values in multiple linear regression models, particularly evident in PMDI-bonded board analysis; second, the sample sizes used in the study are relatively limited, which affects the reliability of model estimation and the universality of study conclusions.

•**Thinking of futher research**

Future research could focus on three key directions: first, exploring various hardwood and softwood species mixing ratios in substrate selection to achieve complementary wood characteristics; second, introducing more process parameters and non-linear model analysis while significantly expanding sample size to enhance statistical reliability; finally, developing customized optimization solutions for different applications while actively exploring new environmentally friendly physical and chemical bonding systems to meet growing environmental requirements and performance demands.

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