ABSTRACT: Eucalyptus wood is one of the important hardwood resources with attractive properties of rapid growth and good quality, which are widely used for the manufacture of wood-based boards, furniture, pulp and paper, and so on. In order to explore the potential of sawdust waste from the eucalyptus wood furniture factory as a bioenergy feedstock, its pyrolysis properties after different solvent extractions were examined using thermogravimetric analysis coupled with Fourier transform infrared spectrometry. The mass ratio of extractives in eucalyptus wood sawdust by benzene−alcohol, hot water, and sodium hydroxide solution was 4.25, 9.68, and 16.11%, respectively. After extraction, the thermal decomposition process of eucalyptus wood was promoted with a higher weight loss rate, lower activation energy, and lower residue content compared to the raw sample without pretreatment, and the promotion level was positively correlated to the strength of extracting solvent. CO₂, CO, CH₄, H₂O, acids, aldehydes, aromatics, ethers, and alcohols were identified as the important intermediates in pyrolysis vapors, which can be tuned by different extraction pretreatments. In terms of typical gas products, benzene−alcohol enhanced the release of carbon dioxide, and hot water enhanced the water generation from dehydration reactions and slightly increased the production of carbon monoxide, while sodium hydroxide promoted the formation of methane at the early stage under 280 °C and later stage over 460 °C during the pyrolysis of eucalyptus wood. It is believed that the extraction pretreatment can not only obtain the bioactive extractive products but also benefit the pyrolysis process by lowering the energy barrier and tuning the composition of pyrolysis products.

1. INTRODUCTION

Due to the shortage of nonrenewable fossil resources and deterioration of ecological environment, more and more interest is being put on the utilization of renewable woody biomass because of its great availability, relatively high energy density, and clean processing properties. Eucalyptus trees are among the most common hardwood species for wood-based board, pulp and paper, bioenergy, and bioproduct production all over the world, especially in Australia, Brazil, China, India, and South Africa.¹⁻³ The attractive properties of eucalyptus trees include rapid growth, excellent properties of wood product and paper produced, and their ability to grow in a wide range of environmental conditions. At present, in China, the existing plantation area of eucalyptus is 4.5 hm², and the eucalypt industry now comprises complex and multifaceted areas, including upstream seedling, planting, harvesting, and transport, and downstream wood processing for multiple products, with around 300 billion CNY for the combined output value of this whole industry.⁴ During the managing, harvesting, and wood processing of eucalypt trees, a great amount of wood wastes is generated, such as branch, bark, sawdust, discarded furniture, floors, and so on, which has great potential as a bioenergy resource of the future in China.

Pyrolysis is one of the advanced bioenergy conversion technologies, which rapidly and efficiently converts the solid biomass waste into high energy density fuel products or materials by thermochemical conditions.⁵⁻⁹ The products of the biomass pyrolysis process typically includes bio-oil, char, and gases, and bio-oil can be upgraded into biofuels or used to make value-added chemicals, while char is a good feedstock of activated carbon, soil amendment, and functional carbonaceous functional materials, and gases can be burned for energy recovery or used to produce syngas.⁶⁻¹⁳ In view of its large
quantity, eucalyptus wood was selected and studied as the raw biomass feedstock of the pyrolysis process for the production of bio-oil and biochar.\textsuperscript{14,17} Eucalyptus wood samples were initially pyrolyzed on a laboratory-scale pyrolysis system at different operating conditions in the ranges of 300–800 °C and 0.050–0.300 L min\textsuperscript{−1}, and the results show that bio-oil derived from eucalyptus wood may be useful for the production of alternative liquid fuels and fine chemicals.\textsuperscript{16} Fast pyrolysis of eucalyptus wood was carried out using different reactor configurations and scale setups.\textsuperscript{18–21} The energy and mass balance in the pyrolysis process of eucalyptus wood were also reported to optimize the technologies.\textsuperscript{22} A life cycle assessment study also demonstrated that the production of bio-oil and activated carbon using a fast pyrolysis process is an eco-friendly option for eucalyptus wood waste management.\textsuperscript{23}

Pretreatment of lignocellulosic biomass has been proven as an important procedure to overcome its intrinsic recalcitrant nature and improve its degradability, which greatly benefits the subsequent conversion process and product quality.\textsuperscript{24,25} Hydrothermal pretreatment was reported to be an effective way of the eucalyptus wood pyrolysis process, which enhanced the bio-oil yield and its levoglucosan contents but reduced the contents of ketones, aldehydes, and organic acids, which helps to improve the fuel quality of bio-oil.\textsuperscript{26,27} The previous studies specifically reported that the extractives show an important effect on the pyrolysis process and properties of pyrolysis products,\textsuperscript{28,29} such as modification in the wood cellulosic structure, inhibiting the levoglucosan formation, decreasing the bio-oil yield, causing phase separation of bio-oil, and so on. Although the current studies made remarkable headways in developing and optimizing the pyrolysis process of eucalyptus wood, the impact of various extraction pretreatments on the pyrolysis properties of eucalyptus wood, especially on the decomposition kinetics and evolution properties of pyrolysis vapors (the precursors for bio-oil and biochar), have not been fully investigated. Moreover, the essential oils and extracts from eucalypt trees were certified as valued bioproducts with antibacterial, antifungal, and even anticancer properties, with a great application prospect in pharmaceutical, cosmetic, food preparations, and leather manufacture.\textsuperscript{30,31} The combination of first separating the extracts for direct utilization and following pyrolysis of pretreated residues is a practical strategy based on a hierarchical biorefinery concept, which not only preserves the activity of extracts but also improves the processability of biomass feedstock.

The purpose of this study is to investigate the impact of different extraction methods on the thermal decomposition behavior, pyrolysis kinetics, and intermediate composition of eucalyptus wood using thermogravimetric analysis coupled with Fourier transform infrared spectroscopy (TG-FTIR). Different solvents of benzene–alcohol, hot water, and NaOH solution were applied as the extracting solution here. It is believed that this study could be meaningful to explore the contribution of extraction pretreatment to the pyrolysis properties of eucalyptus wood, which may have inspirations for multiple thermal–chemical conversion processes.

2. RESULTS AND DISCUSSION

2.1. Decomposition Behavior and Pyrolysis Kinetics. According to Table 2, the mass ratios of extractives in eucalyptus wood by the extraction solvents of benzene–alcohol (BAE), hot water (HWE), and 1% NaOH solution (NaOHE) were 4.25, 9.68, and 16.11%, respectively, which are reasonable and similar to the relative studies. The extractive contents of 10 fast-growing fuelwood species in Costa Rica by ethanol–toluene, hot water, and 1% sodium hydroxide were reported as 0.95–2.84, 2.25–15.28, and 11.08–26.13%, respectively,\textsuperscript{32} with a similar trend as this study. Based on the extractives’ mass ratio, it can be simply concluded that the order for strength of extracting solvents was 1% NaOH solution > hot water > benzene–alcohol. In general, an organic solvent, such as benzene–alcohol here, mainly extracts aliphatic compounds, terpenes, and aromatic compounds.\textsuperscript{33} Besides these compounds, hot water also extracts some starch and small amounts of hemicelluloses. When sodium hydroxide solution was used as the solvent, the aliphatic, terpenes, and aromatic compounds, as well as starch, hemicellulose, and part of soluble lignin fractions, are all extracted out from the biomass feedstock. As mentioned previously in the Introduction part, the extractives from eucalypt wood show the antibacterial activities and phenolic-rich properties, which hold a great potential of being applied in pharmaceutical, cosmetic, leather, and chemical industries.\textsuperscript{30,31}

TG and DTG curves for the pyrolysis characteristics of eucalyptus wood with different extraction pretreatments.
ments are shown in Figure 1. The raw and pretreated eucalyptus wood sawdust has the similar basic decomposition pattern, while some differences were found among the TG-DTG curves of these samples with different weight loss rates and residue contents. A small peak was found in the TG curves of all four samples near 100 °C, which corresponds to the evaporation process of water in air-dried eucalyptus wood. All the four samples uniformly decomposed between 215 and 405 °C and mainly had the maximum thermal weight loss temperature around 350–370 °C. The shoulder peak around 280–320 °C is the decomposition of hemicellulose components in feedstock.

The TG curves of samples were separated to different horizontal values after the main decomposition temperature range, which means that they had different residue contents from 23.2 to 15.4 wt.%. A slight shift of the maximum weight loss temperature from 355 to 362 °C was observed when increasing the strength of extracting pretreatment to the eucalyptus wood, similar to a previous study of hydrothermally pretreatment. It is interesting to point out that the "shoulder" peak of hemicellulose decomposition in the DTG curve at around 290 °C almost disappeared for the sample with 1% NaOH solution extraction, which means that sodium hydroxide solution extracted most of the hemicellulose. In summary, the thermal deconstruction process of eucalyptus wood was activated with a lower residue content and higher weight loss rate by the extraction, and the activation level was positively correlated to the strength of the extracting solvent.

The pyrolysis kinetics parameters of eucalyptus wood with different extraction solvents were calculated by a 3D diffusion model, shown in Table 1. Unextracted eucalyptus wood had an activation energy of 155.8 kJ mol⁻¹ and a frequency factor of 1.14 × 10¹¹ min⁻¹ for its pyrolysis process at a heating rate of 20 °C min⁻¹. As for the other extracted samples, it was found that both the activation energy and the frequency factor significantly decreased as the extracting strength using different extraction solvents was gradually increased. The activated energies of BAE- and HWE-extracted samples were reduced to 143.9 and 134.3 kJ mol⁻¹, respectively, while that of the NaOH-extracted sample dropped down to 111.0 kJ mol⁻¹, nearly 30% lower than that of the pristine eucalyptus wood. In general, activation energy is considered as the minimum average energy requirement that must be overcome before the pyrolysis degradation of the biomass structure can happen and generate pyrolytic products. Therefore, based on the activation energy data, it can be found that the extraction pretreatment reduced the energy barrier and improved the thermal reactivity for the pyrolysis process of pretreated lignocellulosic biomass, which was also verified by the reduced residue content of the samples due to its more severe decomposition behavior after solvent extraction compared to the raw feedstock under the same pyrolysis conditions. It is worth noting that the pre-exponential factor of these pretreated samples varied significantly with different orders of magnitude. The frequency factor is a reflection of the frequency of collisions between reacting molecules, so we may conclude that the pyrolysis of eucalyptus wood after various extraction pretreatments had different cracking reaction frequencies and pathways.

2.2. IR Spectral Analysis of Pyrolysis Intermediates. The evolved volatiles from the TG pyrolysis of eucalyptus wood with different extraction pretreatments were monitored by FTIR in real time (shown in Figure 2). As can be seen from the figures, the evolving profile of gas products during the pyrolysis process was a function of both the wavenumber and temperature. The releasing of gas products mainly focused at the temperatures of from 200 to 400 °C, which corresponded well with the observation of biomass weight loss in Figure 1, except for some CO₂ and CO evolving out at a higher temperature. Raw and three pretreated eucalyptus wood samples with benzene–alcohol, hot water, and NaOH solution had similar patterns with a narrow evolving range and identical IR peaks but with different releasing severities. The benzene–alcohol-pretreated sample was slightly different from other samples due to its specific pyrolysis properties with a unique higher evolving absorbance intensity of gas products at 2320 cm⁻¹. The relative content of carbohydrates in Eucalyptus wood is increased after the extraction pretreatment due to the removal of extract components. When the temperature reached 550 °C, there were still absorbance intensities of several peaks between 2400 and 2150 cm⁻¹ for the three pretreated eucalyptus wood samples. These were assigned to CO₂ and CO evolving out at a higher temperature, which was mainly ascribed to the further cracking and reforming of functional groups inside the volatiles at a later pyrolysis stage. In our case here, the further decomposition of eucalyptus wood samples in the later stage of the pyrolysis process was prompted to happen due to the extraction pretreatment. Interestingly, we believe that this observation may be helpful to explain how extraction pretreatment activates the pyrolysis process of biomass.

Figure 3 shows the representative FTIR spectra of eucalyptus wood samples with different extraction pretreatments when the total released gas reached its highest intensity value. It can be observed that the main pyrolysis products of eucalyptus wood were CO₂, CO, CH₄, H₂O, and organics, such as acids, aldehydes, aromatics, ethers, and alcohols. The absorbance bands of water are located at 3550 and 1350 cm⁻¹. The characteristic bands of CO at 2150 cm⁻¹ and CO₂ at 2250 and 700 cm⁻¹ indicate their formation in this stage. The unique band of 2950 cm⁻¹ stands for the existence of CH₄. The absorbance bands of acids and aldehydes, aromatics, ethers, and alcohols are located at 1750, 1500, and 1100 cm⁻¹.

Table 1. Pyrolysis Kinetics Parameters of Eucalyptus Wood with Different Extraction Pretreatments

| Sample               | Tₘmax (°C) | DTGₘax (wt% 𝑚𝑖𝑛⁻¹) | residue (wt%) | E_a (kJ mol⁻¹) | A (min⁻¹) | R²      |
|----------------------|-----------|---------------------|--------------|---------------|-----------|---------|
| raw wood             | 355       | 21.1                | 23.2         | 155.8         | 1.14 × 10¹² | 0.984   |
| NaOH-extracted       | 360       | 21.3                | 22.5         | 143.9         | 1.09 × 10¹¹ | 0.973   |
| BAE-extracted        | 362       | 24.7                | 16.9         | 134.3         | 1.20 × 10¹⁰ | 0.951   |
| HWE-extracted        | 367       | 28.3                | 15.4         | 111.0         | 6.15 × 10⁹  | 0.950   |

*ₘmax, the temperature corresponding to the maximum DTG value; DTGₘax, the maximum value of derivative thermogravimetry in the DTG curve; E_a, apparent activation energy; A, frequency factor; and R², correlation coefficient.*
respectively. The results of intermediate compounds in pyrolysis vapors obtained in this study are similar to the earlier reports. All the four samples showed the parallel model of the gas product being released at the highest intensity value but with the different relative strengths for some peaks. Benzene–alcohol enhanced the releasing of CO\textsubscript{2} compared to the raw sample, while the hot water and NaOH solution weakened the release of CO\textsubscript{2}. The raw and benzene–alcohol-pretreated samples had more release of carbon monoxide than the others, which may be attributed to the hemicellulose fractions in eucalyptus wood. The release of organic compounds mainly originated from the direct cracking and decomposition of the biomass samples. Acids, aldehydes, ethers, and alcohols were mainly created by the decomposition of carbohydrates, including cellulose and hemicellulose. The IR absorbance intensity of these gas products was reduced as the strength of extracting increased, which confirmed that hot water and sodium hydroxide solution extract more carbohydrates than the benzene–alcohol solvent.

2.3. Typical Gaseous Products Releasing Patterns. Specific FTIR profiles of CO\textsubscript{2}, H\textsubscript{2}O, CH\textsubscript{4}, and CO in pyrolysis vapors of eucalyptus wood with different extraction pretreatments are shown in Figure 4. According to the IR intensities, the amount order for these four gases was CO\textsubscript{2} > H\textsubscript{2}O > CH\textsubscript{4} > CO. The highest release of these gas products was mainly located at a temperature of 350\textdegree–370\textdegree C, which corresponded well with the observation of biomass weight loss in Figure 1 and the 3D IR profiles of gas products in Figure 2.

The release of CO\textsubscript{2} was mainly caused by the cracking and reforming of functional groups of carboxyl (C\textsubscript{\textendash}O) and COOH or the reduction reaction of CO. As can be observed in Figure 2, extraction-pretreated eucalyptus wood samples had a second peak after 550\textdegree C corresponding to the further cracking reactions, and benzene–alcohol extraction-pretreated samples gave the highest release of CO\textsubscript{2}. Water was produced from various kinds of dehydration reactions or polycondensation processes. The dehydration reactions of hot water-pretreated eucalyptus wood during the pyrolysis process were strongly promoted as indicated by its highest yield of water among all the pretreated samples. Methane was mainly formed by the cracking of the methoxy group \textendash OCH\textsubscript{3}\textendash. The breaking of the methylene group \textendash CH\textsubscript{2} also generates methane, which has higher bond energy. The release of CH\textsubscript{4} was weakened to varying degrees by the extraction pretreatment with different solvents. As for the CO, it was mainly released from the cracking of carbonyl (\textendash C\textsubscript{\textendash}O\textendash) and carboxyl (\textendash C\textsubscript{\textendash}=O).
release of CO was slightly enhanced by the extraction pretreatment with benzene−alcohol while weakened by the solvents of hot water and NaOH solution.

Overall, the release of four typical gases is the result of many decomposition reactions, such as decarboxylation, decarbonylation, demethylation, demethoxylation, and dehydration, involved in the biomass pyrolysis process. As indicated by the FTIR-integrated absorbance profiles, benzene−alcohol solvent extraction promoted the production of CO$_2$ by enhancing the decarboxylation reactions and slightly facilitated the generation of CO by enhancing the decarbonylation reactions, while the hot water extraction accelerated the formation of water by promoting the dehydration reactions. As to CH$_4$, sodium hydroxide extraction of feedstock showed a promoted effect on its formation at a low temperature under 280 °C and a high temperature stage over 460 °C while seemingly suppressing it within medium temperature ranges. It is believed that extraction pretreatment not only changed the feedstock composition but also subsequently affected its pyrolysis reaction patterns and routines, showing the capability of tuning the yields of gaseous products in the biomass pyrolysis process.

3. CONCLUSIONS

Based on the hierarchical biorefinery concept, different solvents (benzene−alcohol, hot water, and NaOH solution) were applied to obtain the extractives as a fine bioactive product before subjecting the feedstocks into the pyrolysis process. The mass ratios of extractives in eucalyptus wood sawdust by benzene−alcohol, hot water, and NaOH solution were 4.25, 9.68, and 16.11%, respectively. The pyrolysis kinetic parameters, IR spectra of intermediates, and typical gas product evolving patterns were comparatively studied to examine the impact of different solvent extractions on the pyrolysis properties of eucalyptus wood sawdust. The extraction pretreatment significantly reduced the energy barrier and improved the thermal reactivity of eucalyptus wood sawdust for the pyrolysis process with evidently observed lower activation energy, promoted further cracking progress, and less residue char content, and the promotion level was positively correlated to the strength of the extracting solvent. The main peaks of the IR spectrum from eucalyptus wood pyrolysis were assigned to be CO$_2$, CO, CH$_4$, H$_2$O, acids, aldehydes, aromatics, ethers, and alcohols, and those compounds are believed to be the important intermediates in pyrolysis vapors, which can be tuned by different extraction pretreatments. In terms of typical gas products, benzene−alcohol enhanced the release of carbon dioxide, and hot water enhanced the water generation from dehydration reactions, while the hot water and sodium hydroxide decreased the formation of methane and carbon monoxide at elevated pyrolysis temperatures. This system study is meaningful for exploration of the contribution of extraction pretreatment to the pyrolysis properties of eucalyptus wood, which may also have inspirations for multiple thermal−chemical conversion processes.

4. MATERIALS AND METHODS

4.1. Materials. Eucalyptus (Eucalyptus robusta Smith) wood wastes, namely, sawdust particles, were collected from a wood furniture factory in Guangdong Province, China, which
were generated from the saw cutting procedure of wooden furniture materials. The materials were air dried and screened using a 40–60 mesh. Benzene, alcohol, and sodium hydroxide were purchased from Sinopharm Chemical Reagent Beijing Co., Ltd.

### 4.2. Compositional Analysis of Eucalypt Wood

#### 4.2.1. Ultimate and Proximate Analysis

Carbon, hydrogen, and nitrogen contents of the oven-dried eucalyptus wood sawdust sample were measured automatically using a Vario EL III elemental analyzer. Oxygen content was calculated by the subtraction of the carbon, hydrogen, and nitrogen contents from the total mass of the samples. The proximate analysis was performed with a muffle furnace according to the Chinese National Standard GB/T 212-2008. The moisture, ash, and volatile contents were measured at 105 °C overnight in an oven at 850 °C for 60 min in a muffle furnace and at 900 °C for 7 min in a muffle furnace, respectively. The fixed carbon was determined by the difference between 100% and the sum of the percentages of moisture, volatile, and ash contents. The ultimate and proximate analyses were conducted in triplicate and are shown in Table 2.

| Table 2. Ultimate Analysis and Proximate Analysis of Eucalyptus Wood Waste<sup>a</sup> |
|-----------------------------------------------|-----------------------------------------------|
| **ultimate analysis (wt %)**                 | **proximate analysis (wt %)**                |
| elements                                      |                                               |
| $C_{ad}$                                      | $H_{ad}$                                      |
| value                                         | value                                         |
| 46.36 (0.85)                                  | 5.12 (0.38)                                   |
| $O_{ad}$                                      | 48.35 (0.95)                                  |
| 0.17 (0.03)                                   |                                               |
| $N_{ad}$                                      |                                               |
| 7.23 (0.47)                                   | 82.41 (1.68)                                  |
| moisture<sub>ad</sub>                         | fixed carbon<sub>ad</sub>                    |
| 9.80 (0.63)                                   | ash<sub>ad</sub>                              |
| 0.56 (0.04)                                   |                                               |

<sup>a</sup>$C_{ad}$, air-dried basis; and $O_{ad}$ obtained by difference.

| Table 3. Composition Analysis of Eucalyptus Wood |
|-------------------------------------------------|
| content                                         |
| cellulose (wt %)                                |
| 44.87(1.23)                                     |
| holocellulose (wt %)                            |
| 65.31(2.46)                                     |
| Klason lignin (wt %)                            |
| 23.26(0.82)                                     |
| extractives (wt %)                              |
| benzene–alcohol                                 |
| 4.25(0.36)                                      |
| hot water                                       |
| 9.68(0.71)                                      |
| 1%NaOH                                          |
| 16.11(0.94)                                     |

Figure 4. FTIR-integrated absorbance profiles of typical gas products in pyrolysis vapors obtained from eucalyptus wood with different extraction pretreatments. (a) CO₂, (b) H₂O, (c) CH₄, and (d) CO.
4.2.2. Chemical Composition Analysis. The composition of eucalyptus wood was determined using the methods as follows: first, 2 g of oven-dried eucalyptus wood sawdust was extracted for 6 h in a Soxhlet apparatus by benzene–alcohol (2:1, v/v); then, the extractive-free materials were treated by nitric acid–alcohol (1:4, v/v) solution for the cellulose test, 0.5 mL of glacial acetic acid plus 0.6 g of sodium chloride for holocellulose measurement, and 72% sulfuric acid solution with 3% sulfuric acid solution in sequence for the Klason lignin test, respectively. The composition of eucalyptus wood was performed in triplicate and is summarized in Table 3.

4.3. Extraction Methods. The extracted samples were prepared by a standard extraction process for 6 h in a Soxhlet apparatus with solvents of benzene–alcohol (2:1, v/v), hot water (60 °C), and 1 wt % NaOH solution, which were named as BAE, HWE, and NaOHE, respectively. The extraction-pretreated samples of eucalyptus wood were dried under vacuum for several days and then stored in sealed vials. The content of extractives was directly derived by the weight of residues from the rotary evaporation of extracting liquor. As shown in Table 3, NaOH solution gave the highest yield of extractives followed by hot water, while the lowest yield of extractives was from benzene–alcohol extraction.

4.4. TG-FTIR Analysis. The TG-FTIR instrument applied in this study consists of an NETZSCH STA449F3 thermogravimetric analyzer (TGA) coupled with a Bruker TENSOR 27 FTIR spectrometer. Approximately 8 mg of samples were used in each test. The experiment was carried out on a thermobalance at a linear heating rate of 20 °C·min⁻¹ within the temperature range from the ambient to 850 °C. Nitrogen with a flow rate of 50 mL·min⁻¹ was used for the carrier gas in order to provide an inert atmosphere. The spectrum scope of FTIR was in the range of 500–4000 cm⁻¹, and the resolution factor was selected to be 1 cm⁻¹. TG-FTIR analyses were performed in duplicate for each sample to ensure the validity of the tests.

4.5. Calculation Method of the TG Kinetics. Data from thermogravimetric (TG) and derivative thermogravimetric (DTG) curves were used to determine the kinetic parameters using the Coats and Redfern method and a 3D diffusion model, according to the following methods similar to our previous studies. The Coats and Redfern equation (eq 1), derived from the mathematical analysis by the integral method, is applied as the main formula for the calculation.

\[
\ln \left( \frac{g(\alpha)}{T^2} \right) = \ln \left( \frac{AR}{\beta E} \left( 1 - \frac{2RT}{E} \right) - \frac{E}{RT} \right)
\]

(1)

The parameter \( \alpha \) is the fraction of materials decomposed at time \( t \); \( A \) is the frequency factor; \( E \) is the activation energy of the reaction; \( R \) is the universal gas constant, 8.314462 J·mol⁻¹·K⁻¹; \( T \) is the reaction temperature, K; and \( \beta \) is the heating rate, °C·min⁻¹.

The 3D diffusion model was applied here for the expression form (eq 2) of \( g(\alpha) \) as follows:

\[
g(\alpha) = (1 - (1 - \alpha)^{1/3})^2
\]

(2)

where \( g(\alpha) \) is a function that describes the way the reaction interface occurs throughout the sample.

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**Notes**

The authors declare no competing financial interest.

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