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# Photochemical and enzymatic SET promoted C–C bond cleavage reactions of lignin β-1 model compounds containing varying number of methoxy substituents on their arene rings

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ABSTRACT

In the current study, 1,2-diarylpropan-1,3-diols, containing varying numbers of methoxy substituents that mimic β-1 type units in lignins, were prepared and subjected to photochemical and enzymatic SET oxidative C–C bond cleavage reactions to explore how product distributions and reactivity profiles depend on the numbers and positions of arene ring methoxy-substituents. For this purpose, product distributions of SET-promoted photochemical reactions of the β-1 model compounds and the characteristics of lignin peroxidase catalyzed bond cleavage reactions of these substances were explored. The results show that both the photochemical and enzymatic reactions, which are known to occur by initial SET to form arylpropanoid cation radicals, generate predominantly aldehydes and β-hydroxyketones through cation radical C1–C2 bond cleavage pathways. In addition, analysis of the relative quantum efficiencies of the SET photochemical processes shows that they do not depend greatly on the numbers and positions of arene ring methoxy substituents of the β-1 model compounds.



## 1. Introduction

Because great concerns exist about the depletion of fossil fuels and the environmental impact of their combustion,[1] a large effort has been dedicated to the development of renewable and eco-friendly energy sources. Among several alternatives, bioethanol has attracted great attention as a potential replacement of liquid hydrocarbons.[2–4] Starch, present in grains and cellulose, mainly found in plant cell walls, are bio-sources for this fuel owing to the fact that both are readily transformed by cellulase enzymes to glucose, which is efficiently converted to ethanol by fermentation.

The enzymatic protocols have been adapted to large scale, low energy consuming, and environmentally clean formation of bio-ethanol from starch. However, it is difficult to utilize cellulose for this purpose even though it is abundantly present in otherwise non-consumed plant materials. The major reason for this limitation is associated with the fact that cellulose in plant cell walls is tightly embedded in a complex polymeric network comprised mainly of lignins and, as a result, it is not readily accessed by cellulases.[5–8] Thus, in order to make cellulosic ethanol production cost effective and environmentally friendly, methods are needed to carry out initial cleavage (depolymerization) of the rigid lignin polymeric networks.[9–15]

Lignins possess complex and highly heterogenous arylpropanoid structural backbones.[16–18] A number of different types of structural sub-units are present in these polymers including β-O-4 and spirodienone moieties, the latter of which readily converts to β-1 moieties under mildly acidic conditions (Fig. 1).[19] Moreover, owing to the fact that lignins are biosynthesized by radical polymerization of *p*-hydroxycinnamyl, 4-hydroxy-3-methoxycinnamyl, and 4-hydroxy-3,5-dimethoxycinnamyl alcohol, they contain arylpropanoid moieties with differing degrees of hydroxyl and alkoxyl substitution. Finally, the sub-unit and substituted aryl ring compositions of lignins vary from plant to plant and in some instances they can be controlled through genetic modification.[20]

The identification of heme-iron containing hydrogen peroxide activated lignin peroxidase (LP) and related oxidase enzymes secreted by lignin degrading fungi (e.g., *Phanerochaete chrysosporium*)

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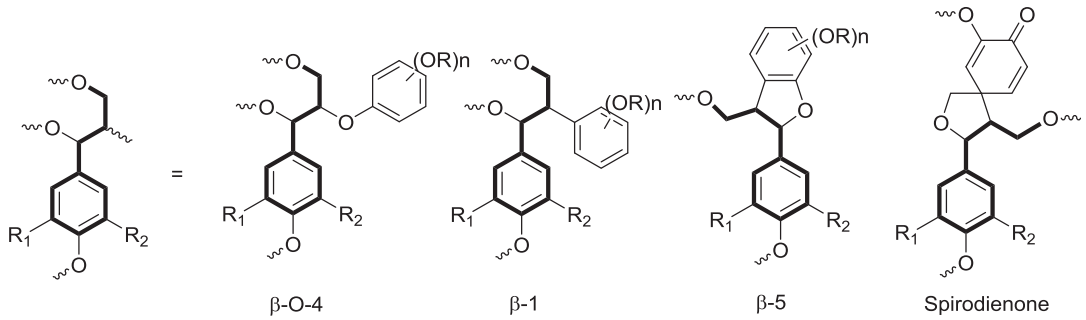


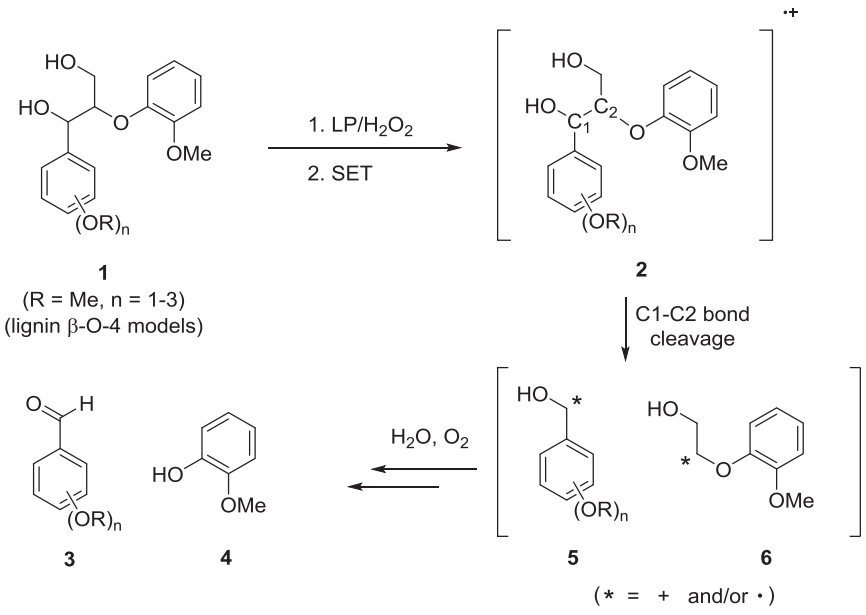

**Fig. 1.** Structural subunits in lignins.

has stimulated a number of studies focused on the use of enzyme catalyzed delignification as part of the cellulosic ethanol production process.[9a,21–23] Especially important in this regard are the results of early mechanistic studies, which demonstrate that LP catalyzes carbon–carbon bond cleavage reactions of substrates that model the β-O-4 and β-1 subunits present in lignins. In addition, observations made in these efforts suggest that single electron transfer (SET) from the lignin models, exemplified by the β-O-4 model **1** in Scheme 1, to the oxidized form of LP is the key event in the pathway(s) for C–C bond cleavage reactions, which are proposed to be involved in the fungi promoted delignification process(es) (Scheme 1). The arene ring localized radical cation intermediates, e.g., **2**, are thought to undergo C1–C2 bond cleavage to produce cation and radical intermediates **5** and **6** that serve as precursors of respective aldehyde and phenol products **3** and **4** observed to form in these reactions.[22c,23a,24–26]

These mechanistic proposals have been verified by using processes that rely on photocatalytic methods for promoting SET oxidation, which generate the same types of C–C bond cleavage derived products.[27–30] In addition, studies[27] have been conducted to gain information about how sub-structural features of lignin models (β-O-4 and β-1) govern the efficiencies of the SET promoted C1–C2 bond cleavage reactions. The results of these experiments along with those arising from DFT bond dissociation energy (BDE) calculations show that radical cations derived from β-1 models (1,2-diarylpropanoid) undergo more efficient C1–C2 bond cleavage than those arising from β-O-4 models (1-aryl-2-oxyarylpropanoid). More recently,[27c] we found that arene ring alkoxy substitution patterns of β-O-4 type lignin model compounds also influence the efficiencies of cation radical C1–C2 bond cleavage reactions.

## 2. Results and discussion

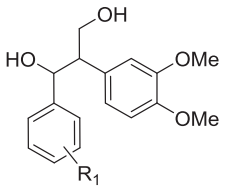
In the continuing studies in this area described below, we investigated the effect of arene ring alkoxy substitution on the efficiencies of C1–C2 bond cleavage reactions of cation radical derived by photochemical and enzymatic SET oxidation of dimeric lignin β-1 model compounds. For this purpose, diastereomerically pure (*erythro* (E) and *threo* (T))[31] diarylpropandiols **10**–**15** (Fig. 2), which contain the β-1 type of arylpropanoid skeleton found in the natural lignins along with varying degrees of arene ring methoxy substitution, were prepared and subjected to SET-photochemical and -lignin peroxidase promoted reactions.



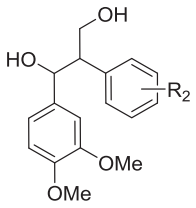

**Scheme 1.**

### 2.1. Synthesis of the β-1 model compounds

The diastereomerically pure β-1 model compounds **10E**–**15E**, **10T**–**13T**, and **15T** were prepared using previously described methods (Scheme 2).[27,31,32] The syntheses of **10E**–**13E** and **10T**–**13T** begin with aldol condensation reactions of corresponding substituted benzaldehydes **16**–**19** and ethyl 3,4-dimethoxyphenylacetate **20**,



**10E, 10T** ($R_1$ = H)
**11E, 11T** ($R_1$ = *p*-OMe)
**12E, 12T** ($R_1$ = *m*, *p*-di(OMe))
**13E, 13T** ($R_1$ = *m*, *m*, *p*-tri(OMe))



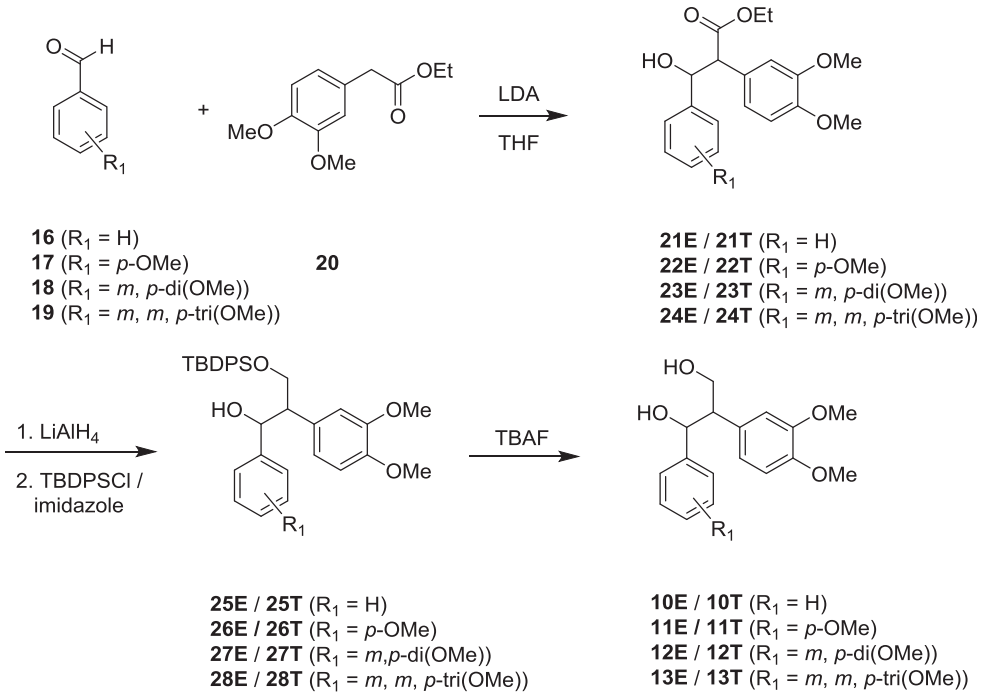
**14E** ($R_2$ = H)
**15E, 15T** ($R_2$ = *p*-OMe)

**Fig. 2.** Lignin β-1 model compounds.

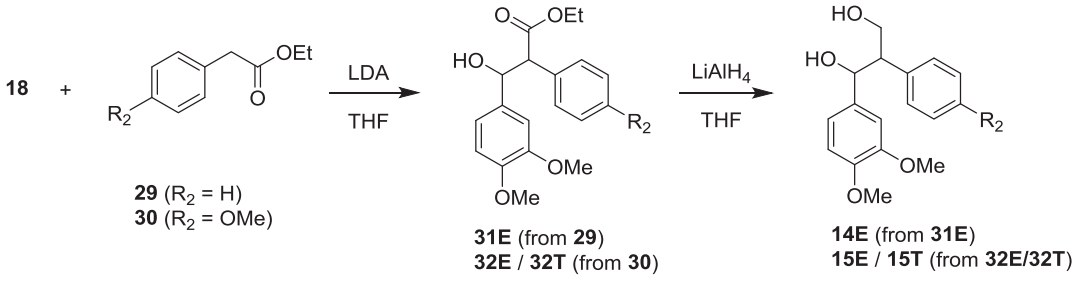
In the routes for preparation of **14E** and **15E**–**15T**, aldehyde **18** was reacted with the corresponding ethyl arylacetate containing different numbers of methoxy substituents (Scheme 3). Reaction of **18** with **29** gave only the *erythro* β-hydroxyester **31E** that was successfully isolated in its pure form. In addition, aldol condensation reaction of **18** with **30** leads to a readily separable mixture of diastereomers **32E** and **32T**. $LiAlH_4$ reductions of **31E**, **32E**, and **32T** generate the respective β-1 model compounds **14E**, **15E**, and **15T**.

### 2.2. 9,10-Dicyanoanthracene (DCA) sensitized photochemical reactions of lignin β-1 model compounds

DCA was used as an excited state electron acceptor to promote photochemical reactions design to explore SET promoted oxidation




**Scheme 2.**




**Scheme 3.**

which in each case produces a mixture of β-hydroxyester diastereomers **21E**–**24E** and **21T**–**24T**. Due to difficulties encountered with isomer separation at this stage, each diastereomer mixture was subjected to $LiAlH_4$ reduction, giving diols, which were then subjected to primary alcohol TBDPS protection. In each case, the mono-TBDPS protected diol stereoisomers are readily separable to give pure samples of **25E**–**28E** and **25T**–**28T**. Finally, desilylation reactions of **25E**–**28E** and **25T**–**28T**, using tetrabutylammonium fluoride (TBAF), give diastereomerically pure lignin β-1 model compounds **10E**–**13E** and **10T**–**13T**, respectively.

of the dimeric lignin β-1 models. In order to show that SET from the lignin models to the singlet excited state of DCA ($E^{S1}_{red}$+2.76 V vs Ag/AgCl)[27c] would be thermodynamically (and thus kinetically) favorable, oxidation potentials of lignin models ($E_{ox}$) and rate of SET ($k_{SET}$) to $DCA^{S1}$ were determined by using the respective CV analysis and fluorescence quenching methods (see Supplementary data). The results, summarized in Table 1, show that oxidation potentials ($E_{ox}$) of all of β-1 models fall in a narrow range around +1.2 V (vs Ag/AgCl) and, importantly, they are well below the singlet excited state reduction potential of DCA ($E^{S1}_{red}$). In addition, quenching of

**Table 1**
Oxidation potentials ($E_{ox}$) and rate constants ($k_{SET}$) for SET quenching of DCA of the lignin model compounds **10E**–**15E**, **10T**–**13T**, and **15T**

| Substrate | $E_{ox}$ (+) (V vs Ag/AgCl) | $k_{SET}\times10^{-10}$ ($M^{-1}$ $s^{-1}$) | Substrate | $E_{ox}$ (+) (V vs Ag/AgCl) | $k_{SET}\times10^{-10}$ ($M^{-1}$ $s^{-1}$) |
|---|---|---|---|---|---|
| **10E** | +1.19 | 0.91 | **10T** | +1.19 | 0.99 |
| **11E** | +1.18 | 1.08 | **11T** | +1.16 | 1.08 |
| **12E** | +1.22 | 1.16 | **12T** | +1.18 | 1.24 |
| **13E** | +1.18 | 0.82 | **13T** | +1.15 | 1.06 |
| **14E** | +1.17 | 0.73 | — | — | — |
| **15E** | +1.12 | 0.86 | **15T** | +1.17 | 1.04 |

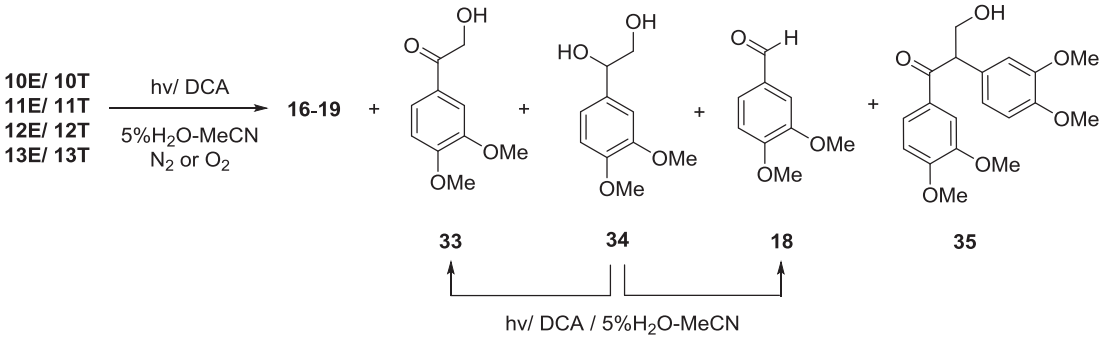
DCA fluorescence the by all β-1 models **10E**–**15E**, **10T**–**13T**, and **15T** takes place at near diffusion controlled rates in the range of $7\times10^{9}$–$10^{10}$ $M^{-1}$ $s^{-1}$ as is expected for exergonic SET.[33]

SET promoted photochemical reactions of the β-1 models **10E**–**15E**, **10T**–**13T**, and **15T** were carried out on 5% aqueous MeCN solutions containing DCA under either a $N_2$ (28 h) or $O_2$ (7 h) atmosphere environments by irradiation with light of wavelengths >330 nm that are absorbed by DCA. As can be seen by viewing the results displayed in Schemes 4 and 5, and Table 2, DCA induced

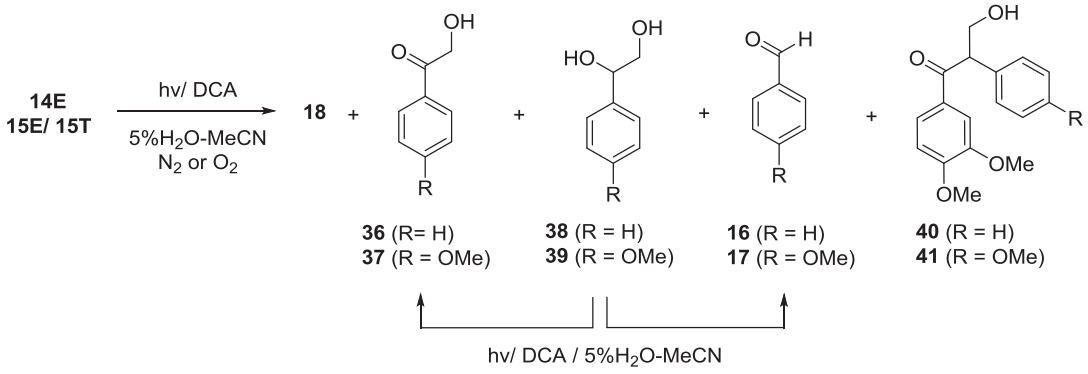
**Table 2**
Products and yields of DCA-promoted photochemical reactions of lignin β-1 model compounds carried out under $N_2$ atmosphere[a]

| Substrate | % Conversion[b] | Products[c] (%) |
|---|---|---|
| **10E** | 18 | **16** (9), **18** (1), **33** (trace), **34** (trace) |
| **10T** | 13 | **16** (9), **18** (1), **33** (trace), **34** (trace) |
| **11E** | 28 | **17** (15), **18** (1), **33** (trace), **34** (trace) |
| **11T** | 18 | **17** (14), **18** (2), **33** (trace), **34** (trace) |
| **12E** | 29 | **18** (22), **33** (9), **34** (trace), **35** (trace) |
| **12T** | 28 | **18** (21), **33** (10), **34** (trace), **35** (2) |
| **13E** | 29 | **19** (12), **18** (1), **33** (trace), **34** (trace) |
| **13T** | 23 | **19** (11), **18** (1), **33** (trace), **34** (trace) |
| **14E** | 22 | **18** (7), **16** (trace), **36** (trace), **37** (trace) |
| **15E** | 18 | **18** (13), **17** (2), **37** (trace), **39** (trace), **41** (3) |
| **15T** | 16 | **18** (13), **17** (trace), **37** (1), **39** (trace), **41** (trace) |

[a] Solutions containing substrate (2.1 mM) and satd DCA (0.27 mM) were irradiated for the same time period (28 h).
[b] Based on recovered starting substrates, determined by HPLC analysis.
[c] Determined by HPLC analysis.




**Scheme 4.**




**Scheme 5.**

photoreactions of β-1 models taking place under deoxygenated conditions ($N_2$) give rise to the formation of benzaldehyde derivatives arising from both the C1 (major) and C2 (minor) arene rings, along with trace amounts of 1,3-diols and α-hydroxyacetophenone derivatives, all of which arise by C1–C2 bond cleavage processes. Interestingly, in photoreactions of **12E** and **12T** and **15E** and **15T**, which contain di-methoxy substituted C1-arene rings, the corresponding benzylic C1–H bond cleavage products **35** and **41** are produced in trace amounts in addition to the C1–C2 bond cleavage products (i.e., aldehydes **17**–**18**, 1,3-diol **34**, and α-hydroxyketone **33**). Based on the additional observations that DCA promoted photoreactions of 1,3-diols **34** and **38**–**39** lead to formation of the respective aldehydes **16**–**18** and α-hydroxyketones **33**, **36**–**37** (Schemes 4 and 5) the major benzaldehyde derivatives produced in SET photoreactions arise from the C-1 arene ring through primary SET events and the minor (<1%) benzaldehyde derivatives arise from the C-2 arene ring through secondary photoreactions of the initially formed 1,3-diol photoproducts.

DCA promoted photoreactions of the lignin β-1 models in an $O_2$ environment were observed to take place more efficiently than those carried out under $N_2$ as judged by the irradiation time required to bring about the same or higher levels of conversion (Schemes 4 and 5, and Table 3).[15a,34–36] In a manner that is similar

**Table 3**
Products and yields of DCA-promoted photochemical reactions of lignin β-1 model compounds carried out under $O_2$ atmosphere[a]

| Substrate | % Conversion | Products[b] (%) |
|---|---|---|
| **10E** | 100 | **16** (51), **18** (25), **33** (q.l),[c] **34** (q.l)[c] |
| **10T** | 100 | **16** (53), **18** (23), **33** (11), **34** (q.l)[c] |
| **11E** | 100 | **17** (78), **18** (34), **33** (15), **34** (q.l)[c] |
| **11T** | 100 | **17** (80), **18** (26), **33** (10), **34** (q.l)[c] |
| **12E** | 100 | **18** (98), **33** (26), **34** (trace), **35** (q.l)[c] |
| **12T** | 100 | **18** (98), **33** (23), **34** (trace), **35** (q.l)[c] |
| **13E** | 100 | **19** (40), **18** (24), **33** (12), **34** (q.l)[c] |
| **13T** | 100 | **19** (50), **18** (30), **33** (15), **34** (q.l)[c] |
| **14E** | 100 | **18** (23), **16** (15), **36** (6), **38** (q.l),[c] **40** (7) |
| **15E** | 100 | **18** (33), **17** (16), **37** (8), **39** (q.l),[c] **41** (q.l)[c] |
| **15T** | 100 | **18** (32), **17** (18), **37** (6), **39** (q.l),[c] **41** (q.l)[c] |

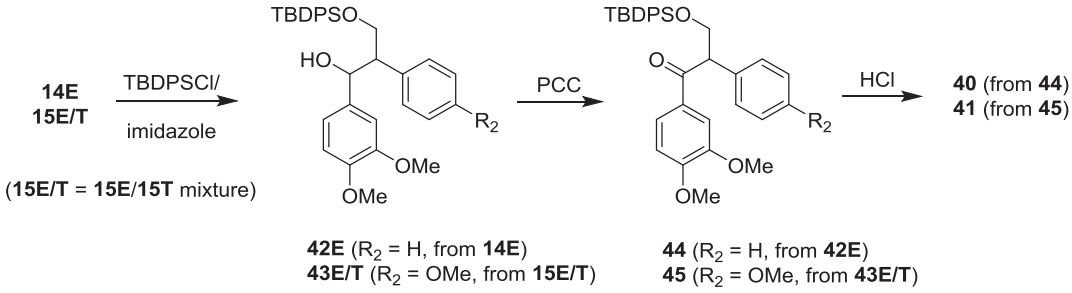
[a] Solutions containing substrate (2.1 mM) and satd DCA (0.27 mM) were irradiated for the same time period (7 h).
[b] Determined by HPLC analysis.
[c] Quantification limit (q.l) from the HPLC analysis.

**Table 4**
Products and yields of LP-catalyzed reactions of β-1 lignin model compounds[a]

| Substrate | % Conversion | Products[b] (%) |
|---|---|---|
| **10E** | 46 | **16** (30), **18** (11), **33** (10), **34** (q.l)[c] |
| **10T** | 44 | **16** (32), **18** (8), **33** (10), **34** (q.l)[c] |
| **11E** | 36 | **17** (33), **18** (9), **33** (10), **34** (q.l)[c] |
| **11T** | 35 | **17** (33), **18** (9), **33** (10), **34** (q.l)[c] |
| **12E** | 36 | **18** (25), **33** (6), **34** (q.l),[c] **35** (q.l)[c] |
| **12T** | 32 | **18** (24), **33** (8), **34** (q.l),[c] **35** (q.l)[c] |
| **13E** | 37 | **19** (21), **18** (7), **33** (9), **34** (q.l)[c] |
| **13T** | 34 | **19** (23), **18** (7), **33** (8), **34** (q.l)[c] |
| **14E** | 39 | **18** (21), **16** (2), **36** (15), **38** (q.l),[c] **40** (10) |
| **15E** | 14 | **18** (8), **17** (3), **37** (1), **39** (q.l),[c] **41** (q.l)[c] |
| **15T** | 15 | **18** (11), **17** (4), **37** (4), **39** (q.l),[c] **41** (q.l)[c] |

[a] Solution containing substrate (0.4 mM) and LP (8 μM) and 60 μL of $H_2O_2$ were used.
[b] Determined by HPLC analysis.
[c] Quantification limit (q.l) from the HPLC analysis.

to those occurring under $N_2$, photoreactions in $O_2$ saturated solutions give rise to formation of benzaldehyde derivatives arising from both the C1 (major) and C2 (minor) arene rings, along with trace amounts of 1,3-diols and α-hydroxyacetophenone derivatives. In addition, photoreactions in the presence of $O_2$ produce β-hydroxyketones **35** and **40**–**41** derived from benzylic C1–H bond cleavage process as minor products. Structural determinations of **40** and **41** were made by comparison with authentic samples independently prepared by selective benzylic oxidation of **14E** and **15E**, respectively, and **35**[27a] is a known substance (Scheme 6).




**Scheme 6.**

## 2.3. Lignin peroxidase (LP) catalyzed reactions of β-1 model compounds

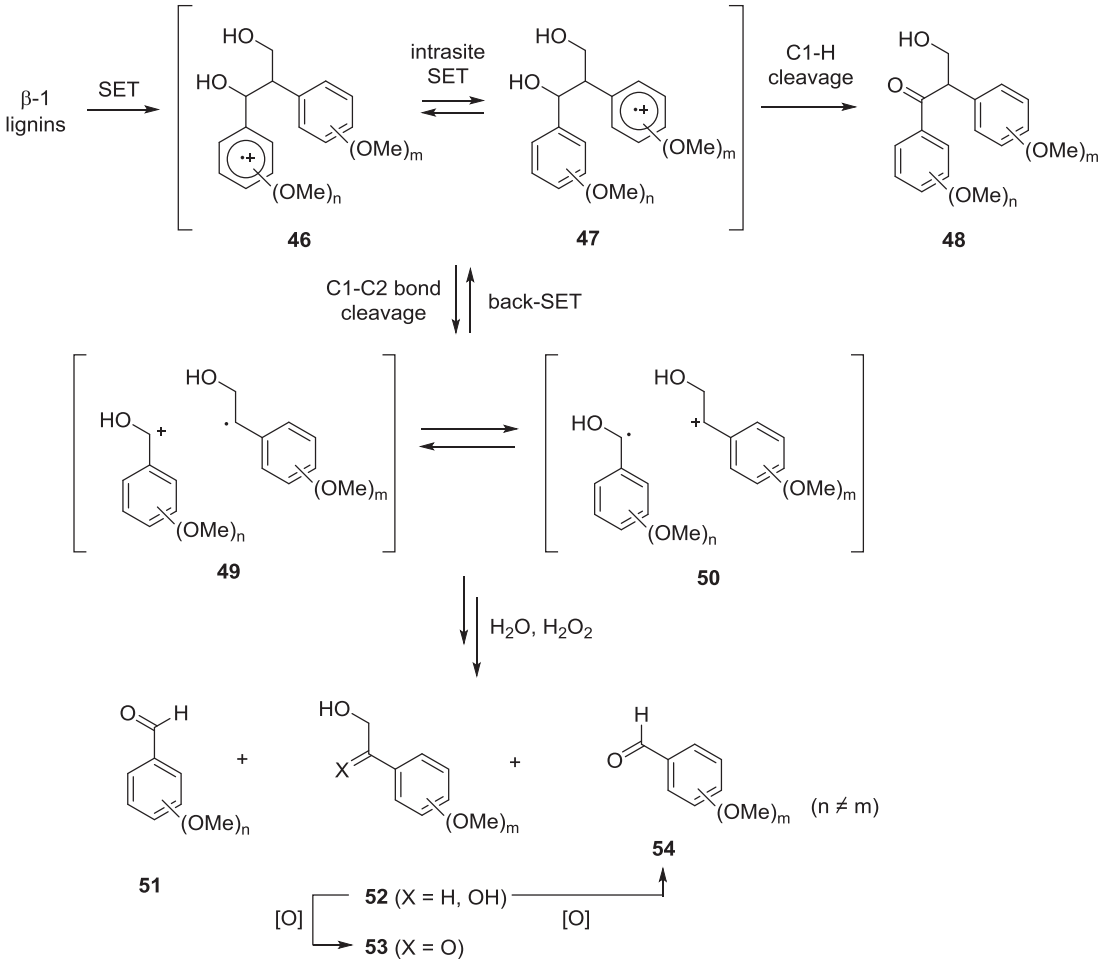
LP catalyzed oxidation reactions of β-1 lignin model compounds in the presence of $H_2O_2$ were carried out for fixed time periods of 30 min. Analysis of the product distributions and yields of these reactions (Table 4) show that **10E**–**15E**, **10T**–**13T**, and **15T** generate the corresponding aldehydes **16**–**19**, 1,3-diols **34**, **38**–**39**, and α-hydroxyketones **33**, **36**–**37** through C1–C2 bond cleavage pathways. Like those in the DCA-promoted photoreactions, yields of aldehydes derived from the C-2 arene ring are relatively much lower than those that arise from C-1 arene ring. In the absence of LP, reactions of β-1 lignin model compounds with $H_2O_2$ do not take place.

## 2.4. Mechanistic analysis

Based upon the product distributions displayed above coupled with insights provided earlier,[23–27] plausible mechanisms can be outlined for the SET photochemical and LP catalyzed reactions of the β-1 lignin model compounds (Scheme 7). In each process, thermodynamically favorable SET takes place from the arene moieties in the model compound to the corresponding electron acceptor ($DCA^{S1}$ or $H_2O_2$-activated LP) to form the key radical cation intermediate, represented by **46** and **47**, which could be either rapidly interconverting species or resonance structures depending upon the equivalence or non-equivalence of their nuclear coordinates (see below). The radical cation then undergoes C1–C2 bond cleavage to produce either one of two or both cation-radical pairs **49** and **50**, which again might rapidly interconvert through SET (see below). Loss of a proton from the C-1 arene ring derived hydroxymethyl cation in **49** or oxidation of the benzylic radical in **50** then yields the major product, benzaldehyde **51**. Capture by water of the C-2 arene derived cation in **50** generates the diol **52**. Formation of β-hydroxyketone **48** in only trace quantities is a consequence of inefficiently competitive benzylic C1–H deprotonation of radical cation **46**. Finally, secondary oxidation reactions of 1,3-diol **52** serve as the origins of the C-2 arene ring derived minor aldehyde **54** and α-hydroxyketones **53**.[27a]

## 2.5. Relative efficiencies of DCA promoted SET oxidation reactions of β-1 model compounds

As can be seen from mechanistic analysis summarized in Scheme 7, the radical cation of the β-1 lignin model compound, generated by SET to $DCA^{S1}$ undergoes C1–C2 bond cleavage in the primary event leading to formation of aldehyde and diol photoproducts. Importantly, C1–C2 bond cleavage competes with back-SET from the DCA anion radical to the β-1 model derived cation radical. Because the rates of SET from the β-1 models to $DCA^{S1}$ are nearly equal (see Table 1) and the rates of back-SET are also expected to be equal, the relative rates of cation radical C1–C2 bond cleavage should govern the relative quantum efficiencies of these SET promoted bond cleavage processes. Thus, it should be possible




**Scheme 7.**

to gain information about the relative rates of cation radical C1–C2 bond cleavage by determining the relative efficiencies of these photoreactions as reflected in the formation of the major, C-1 arene ring derived benzaldehyde products.

To gain information about the effects of arene ring methoxy substitution on the rates of cation radical C1–C2 arene ring cleavage in the β-1 model compounds, relative quantum efficiencies ($\Phi_{rel}$) of DCA promoted photoreactions were determined by measuring yields of C1-arene ring derived benzaldehyde formation in low conversion (<20%) photoreactions carried out under identical conditions. For this purpose, DCA saturated, $N_2$ purged solutions containing each lignin model compound ($1.5\times10^{-5}$ mol, 2.1 mM) in 7 mL of 5% aqueous MeCN in quartz tubes were simultaneously irradiated by using uranium filtered light ($\lambda$>330 nm) in a merry-go-round apparatus for 6 h. Aldehyde yields were then determined by using HPLC analysis of the crude photolysates and then converted to relative quantum yields ($\Phi_{rel}$) by setting the quantum efficiency for reaction of **11T** (in Table 5) to be unity. The results show that the numbers and position of arene ring methoxy substituents of β-1 model compounds do not have a large effect on relative quantum efficiencies. However, non-methoxy substituted substrate, especially **14E**, undergoes C1–C2 bond cleavage reactions with the lowest efficiency.

**Table 5**
Relative quantum yield ($\Phi_{rel}$) of DCA promoted photoreactions of **10E**–**15E** and **10T**–**13T**

| Substrate | $\Phi_{rel}$ | Substrate | $\Phi_{rel}$ |
|---|---|---|---|
| **10E** | 0.5 | **10T** | 0.4 |
| **11E** | 0.9 | **11T** | 1.0 |
| **12E** | 0.8 | **12T** | 0.7 |
| **13E** | 0.6 | **13T** | 0.7 |
| **14E** | 0.2 | | |
| **15E** | 0.5 | | |

## 2.6. DFT calculations

In order to gain an understanding of several features of the SET promoted C–C bond cleavage reactions of cation radicals derived from the β-1 model compounds **10E**–**13E**, DFT calculations were performed using the B3LYP method with Gaussian 09 and the 6-31+G(d,p) basis set. The results of this treatment are summarized in Fig. 3, where the geometry optimized/energy minimized structures, and positive charge and odd electron (spin) density distributions are displayed. In addition, owing to their potential relationship to rates of cation radical bond cleavage, bond dissociation energies (BDE) of the neutral model compounds and those for C1–C2 bond cleavage of the corresponding radical cations associated with formation of C1-cation/C2-radical or C1 radical/C2 cation pairs were calculated using this method (Table 6). As anticipated, cation radical arising from SET oxidation of the β-1 model compounds have positive charge and odd electron densities distributed throughout both the C1 and C2 arene rings in a manner that is dependent on the degree of methoxy substitution in these moieties. This is demonstrated by a comparison of the radical cation of **10E**, where positive charge and odd electron densities are delocalized mainly in the dimethoxy-substituted C2 arene ring, while

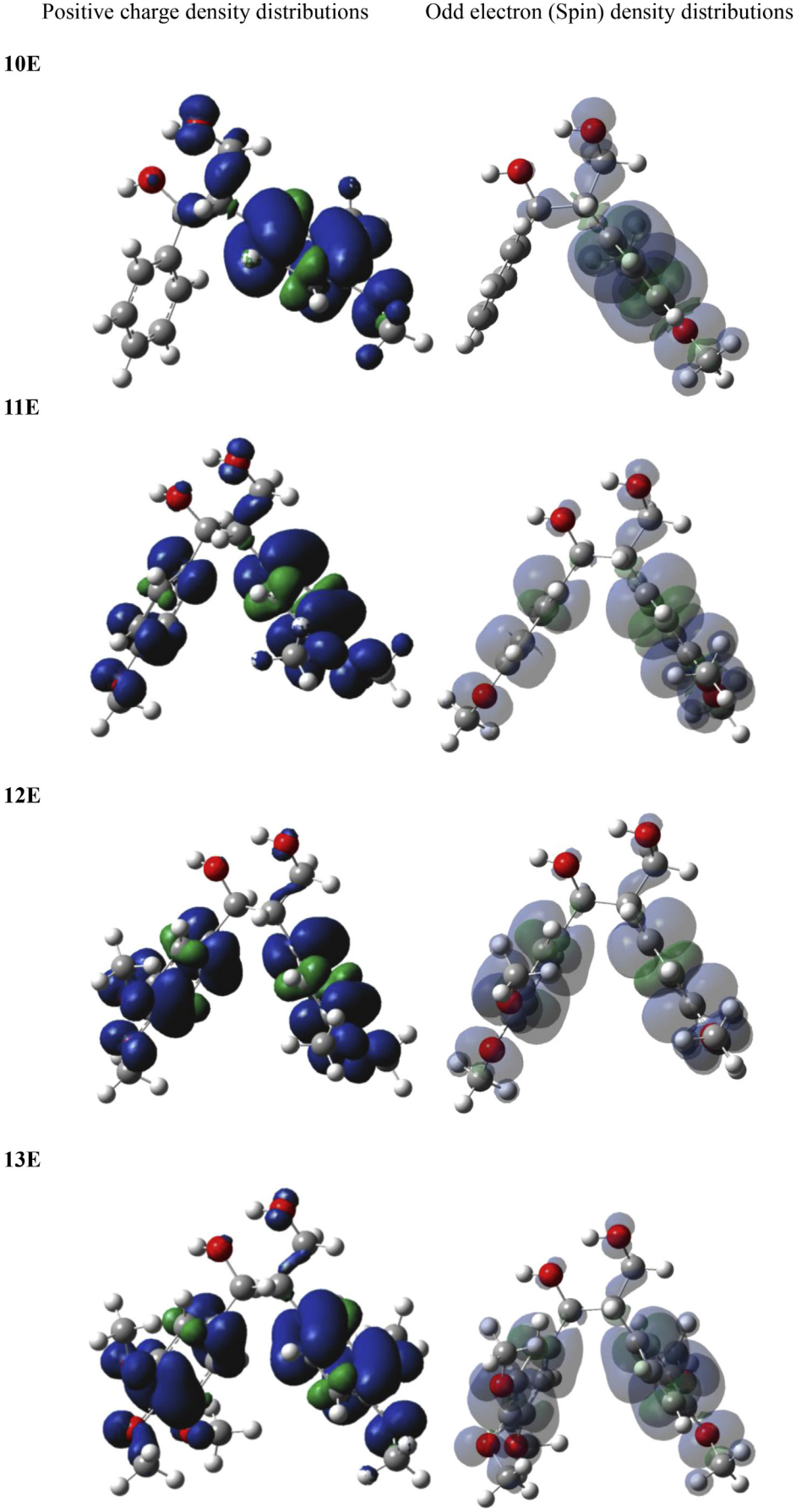



**Fig. 3.** DFT calculated, positive charge (left) and odd electron (right) density distributions of energy minimized radical cation structures derived from **10E**–**13E**. Isosurfaces correspond to 0.02 au.

**Table 6**
DFT calculated C1–C2 bond dissociation energies (BDE) of **10E**–**15E**

| Models | BDE of neutral models (kcal/mol) | BDE of radical cations forming | |
|---|---|---|---|
| | | C1 cation+C2 radical (kcal/mol) | C1 radical+C2 cation (kcal/mol) |
| **10E** | 53.7 | 34.2 | 26.4 |
| **11E** | 54.4 | 24.3 | 29.1 |
| **12E** | 54.2 | 25.1 | 33.3 |
| **13E** | 54.1 | 24.7 | 33.1 |

those for **11E**–**13E** have these densities on distributed both of the arene rings (Fig. 3). In addition, the observation that the energy changes involved in cation radical C1–C2 bond cleavage are lower than those of the neutral analogs, reflected in BDEs (Table 6), match the experimentally observed nature of SET promoted reactions of the β-1 model compounds. Finally, energy changes associated with cation radical C1–C2 bond cleavage are dependent on the direction of positive charge and odd electron flow in these processes. Specifically, the results show that the choice between C1-cation/C2-radical and C1 radical/C2 cation production is influenced by the energies (stabilities) of the cations and radicals generated. Thus, the BDE for cleavage of the cation radical of **10E** to form the dimethoxy-substituted C2 benzylic cation is lower than that for production of the unsubstituted α-hydroxy-benzylic cation, whereas in the cases of **11E**–**13E** the BDEs for C1–C2 cleavage are lower for generation of the increasingly methoxy-substituted C1 α-hydroxy-benzylic cations.

Finally, although the trends only partially match those associated with the indirectly determined rates of C1–C2 bond cleavage (Table 5), the calculated cation radical BDEs display trends that indicate a dependence on the degree of arene ring methoxy-substitution. However, at this point it is premature to conclude that the relative quantum yields for SET promoted photoreactions of **10E**–**13E** are directly related to cation radical BDEs.

## 3. Conclusion

In the study described above, methoxy substituted 1,2-diarylpropan-1,3-diols that mimic β-1 type units in lignins were prepared and subjected to photochemical and enzymatic SET oxidative C–C bond cleavage reactions. The aim was to explore how product distributions and reactivities depend on the numbers and positions of arene ring methoxy-substituents. The results show that both photochemical and enzymatic reactions of these substances, which are known to take place by initial SET to form arylpropanoid cation radicals, generate predominantly aldehydes and β-hydroxyketones through cation radical C1–C2 bond cleavage pathways. In addition, analysis of the relative quantum efficiencies of the SET photochemical processes shows that they do not depend greatly on the numbers and positions of methoxy substituents on the arene rings of the β-1 model compounds.

## 4. Experimental

### 4.1. Diastereomeric 21E and 21T

A solution of diisopropylamine (5.7 mL, 40.0 mmol) in dry THF (40 mL) containing 16 mL (40.0 mmol) of 2.5 M *n*-BuLi at −78 °C was stirred for 30 min. Acetate ester **20** (9.0 g, 40.0 mmol) was then added dropwise and the resulting solution was stirred over for 1 h followed by addition of benzaldehyde **16** (4.0 g, 37.7 mmol). After 3 h additional stirring at the same temperature, the mixture was diluted with $H_2O$ and extracted with EtOAc. The organic layer was dried and evaporated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield *erythro* **21E** (5.8 g, 47%) and *threo* **21T** (2.9 g, 23%) in 2:1 ratio as diastereomeric mixture ratio.

*4.1.1.* ***21E*** *(diastereomeric mixture, l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.20 (t, 3H, $J$=7 Hz), 3.66 (s, 3H), 3.76 (s, 1H), 3.77 (s, 3H), 4.10–4.25 (m, 2H), 5.08 (d, 1H, $J$=9.5 Hz), 6.48 (s, 1H), 6.63 (q, 2H, $J$=8 Hz), 7.06–7.31 (m, 5H); $^{13}$C NMR ($CDCl_3$) $\delta$ 14.0, 55.6, 59.5, 61.1, 76.6, 110.8, 111.7, 120.6, 126.6, 127.1, 127.6, 128.0, 140.9, 148.2, 148.5, 173.5; HRMS (ES) $m/z$ 353.1362 (M+Na, $C_{19}H_{22}O_5Na$ requires 353.1365).

*4.1.2.* ***21T*** *(diastereomeric mixture, sol mp 82 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 1.00 (t, 3H, $J$=7 Hz), 3.74 (s, 1H), 3.80 (s, 3H), 3.83 (s, 3H), 3.90–4.01 (m, 2H), 5.20 (d, 1H, $J$=8 Hz), 6.79–6.89 (m, 3H), 7.06–7.31 (m, 5H); $^{13}$C NMR ($CDCl_3$) $\delta$ 13.8, 55.7, 59.2, 60.8, 75.2, 110.9, 111.9, 121.3, 126.7, 127.1, 127.9, 128.0, 140.8, 148.6, 148.8, 172.4; HRMS (ES) $m/z$ 353.1362 (M+Na, $C_{19}H_{22}O_5Na$ requires 353.1365).

### 4.2. Diastereomeric 22E and 22T

A solution of diisopropylamine (5.7 mL, 40.0 mmol) in dry THF (40 mL) containing 16 mL (40.0 mmol) of 2.5 M *n*-BuLi at −78 °C was stirred for 30 min. Acetate ester **20** (9.0 g, 40.0 mmol) was then added dropwise and the resulting solution was stirred over for 1 h followed by addition of *p*-anisaldehyde **17** (5.1 g, 37.7 mmol). After 3 h additional stirring at the same temperature, the mixture was diluted with $H_2O$ and extracted with EtOAc. The organic layer was dried and evaporated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield *erythro* **22E** (8.2 g, 60%) and *threo* **22T** (2.0 g, 15%) in 4:1 ratio as diastereomeric mixtureratio.

*4.2.1.* ***22E*** *(diastereomeric mixture, l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.20 (t, 3H, $J$=7.5 Hz), 3.68 (s, 6H), 3.73 (s, 1H), 3.76 (s, 3H), 4.09–4.23 (m, 2H), 5.04 (d, 1H, $J$=9.5 Hz), 6.51 (s, 1H), 6.58–6.68 (m, 4H), 6.98 (d, 2H, $J$=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 14.0, 55.0, 55.6, 55.6, 59.5, 61.0, 76.2, 110.7, 111.6, 120.6, 127.7, 127.9, 133.1, 148.1, 148.5, 158.9, 173.5; HRMS (ES) $m/z$ 383.1466 (M+Na, $C_{20}H_{24}O_6Na$ requires 383.1471).

*4.2.2.* ***22T*** *(diastereomeric mixture, sol mp 124 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 1.00 (t, 3H, $J$=7 Hz), 3.71 (s, 1H), 3.74 (s, 3H), 3.81 (s, 3H), 3.83 (s, 3H), 3.89–3.99 (m, 2H), 5.13 (d, 1H, $J$=8 Hz), 6.79–6.81 (m, 3H), 6.87–6.90 (m, 2H), 7.22 (s, 2H); $^{13}$C NMR ($CDCl_3$) $\delta$ 13.8, 55.1, 55.6, 55.7, 59.3, 60.7, 74.8, 111.0, 111.8, 113.5, 121.3, 127.4, 127.7, 133.1, 148.6, 148.8, 159.2, 172.3; HRMS (ES) $m/z$ 383.1466 (M+Na, $C_{20}H_{24}O_6Na$ requires 383.1471).

### 4.3. Diastereomeric 24E and 24T

A solution of diisopropylamine (5.7 mL, 40.0 mmol) in dry THF (40 mL) containing 16 mL (40.0 mmol) of 2.5 M *n*-BuLi at −78 °C was stirred for 30 min. Acetate ester **20** (9.0 g, 40.0 mmol) was added dropwise and the resulting solution was stirred over for 1 h followed by addition of 3,4,5-trimethoxybenzaldehyde **19** (7.4 g, 37.7 mmol). After 3 h additional stirring at the same temperature, the mixture was diluted with $H_2O$ and extracted with EtOAc. The organic layer was dried and evaporated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield *erythro* **24E** (8.9 g, 56%) and *threo* **24T** (2.2 g, 14%) in 4:1 ratio as diastereomeric mixtureratio.

*4.3.1.* ***24E*** *(diastereomeric mixture, l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.21 (t, 3H, $J$=7.5 Hz), 3.66 (s, 6H), 3.69 (s, 1H), 3.71 (s, 3H), 3.73 (s, 3H), 3.78 (s, 3H), 4.11–4.26 (m, 2H), 5.02 (d, 1H, $J$=9.5 Hz), 6.25 (s, 2H), 6.51–6.68 (m, 3H); $^{13}$C NMR ($CDCl_3$) $\delta$ 14.0, 55.8, 55.9, 56.0, 59.6, 60.7, 61.2, 75.3, 103.4, 110.9, 111.7, 120.8, 127.7, 136.5, 137.2, 148.4,

148.7, 152.7, 173.5; HRMS (ES) *m*/*z* 443.1678 (M+Na, $C_{22}H_{28}O_8Na$ requires 443.1682).

*4.3.2.* ***24T*** *(diastereomeric mixture, sol mp 103 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 1.05 (t, 3H, *J*=7 Hz), 3.72 (s, 1H), 3.82 (s, 9H), 3.84 (s, 3H), 3.88 (s, 3H), 3.92–4.07 (m, 2H), 5.13 (d, 1H, *J*=7.5 Hz), 6.53 (s, 2H), 6.79–6.87 (m, 3H); $^{13}$C NMR ($CDCl_3$) $\delta$ 13.9, 55.7, 55.9, 56.0, 59.2, 60.9, 61.2, 75.3, 103.7, 111.0, 111.9, 121.5, 127.0, 136.4, 137.5, 148.8, 148.9, 152.9, 172.5; HRMS (ES) *m*/*z* 443.1678 (M+Na, $C_{22}H_{28}O_8Na$ requires 443.1682).

### 4.4. Diastereomeric 25E and 25T

To respective solutions of THF containing 1.0 M $LiAlH_4$ (9.5 mL, 9.5 mmol) were added mixture of **21E** and **21T** (3.15 g, 9.5 mmol) at room temperature. After stirring for 3 h, 15 mL $H_2O$ and 15 mL 1 N HCl solution at 0 °C were added and the solutions were extracted with $CH_2Cl_2$. The extracts were dried and concentrated in vacuo to afford mixture of **10E**/**10T**. A mixture solution of **10E**/**10T** (1.5 g, 5.2 mmol) in DMF 50 mL containing imidazole (0.9 g, 13.0 mmol) and *tert*-butyldiphenylsilylchloride (1.45 g, 5.3 mmol) was stirred for 10 h at room temperature and concentrated in vacuo to give a residue, which was partitioned between $CH_2Cl_2$ and $H_2O$. The organic layer was dried and concentrated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield **25E** (1.23 g, 45%) and **25T** (0.55 g, 20%).

*4.4.1.* ***25E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.08 (s, 9H), 3.03–3.07 (m, 1H), 3.62 (s, 3H), 3.77 (s, 3H), 4.00–4.03 (m, 1H), 4.13–4.17 (m, 1H), 4.31 (s, 1H), 5.11 (dd, 1H, *J*=2.5, 8 Hz), 6.35 (s, 1H), 6.51 and 6.62 (d, 2H, *J*=8.5 Hz), 7.13–7.18 (m, 5H), 7.25–7.44 (m, 6H), 7.61–7.66 (m, 4H); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.1, 26.9, 54.0, 55.7, 55.7, 67.7, 78.5, 110.7, 112.3, 120.5, 126.7, 127.1, 127.8, 129.9, 129.9, 131.7, 132.6, 135.6, 135.6, 142.9, 147.7, 148.4; HRMS (ES) *m*/*z* 549.2433 (M+Na, $C_{33}H_{38}O_4SiNa$ requires 549.2437).

*4.4.2.* ***25T*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.03 (s, 9H), 3.02–3.06 (m, 1H), 3.68 (s, 3H), 3.73–3.76 (m, 1H), 3.84 (s, 3H), 3.88–3.91 (m, 1H), 5.25 (dd, 1H, *J*=1, 4.5 Hz), 6.58 (s, 1H), 6.70 and 6.75 (d, 2H, *J*=8.5 Hz), 7.20–7.38 (m, 11H), 7.48–7.52 (m, 4H); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.2, 26.9, 54.9, 55.7, 55.8, 65.4, 74.5, 110.9, 112.8, 121.3, 126.6, 127.4, 127.6, 128.0, 131.1, 133.1, 135.5, 142.4, 148.0, 148.5; HRMS (ES) *m*/*z* 549.2427 (M+Na, $C_{33}H_{38}O_4SiNa$ requires 549.2437).

### 4.5. Diastereomeric 26E and 26T

To respective solutions of THF containing 1.0 M $LiAlH_4$ (9.4 mL, 9.4 mmol) were added mixture of **22E** and **22T** (3.4 g, 9.4 mmol) at room temperature. After stirring for 3 h, 15 mL $H_2O$ and 15 mL 1 N HCl solution at 0 °C were added and the solutions were extracted with $CH_2Cl_2$. The extracts were dried and concentrated in vacuo to afford mixture of **11E**/**11T**. A mixture solution of **11E**/**11T** (0.9 g, 2.8 mmol) in DMF 40 mL containing imidazole (0.47 g, 6.9 mmol) and *tert*-butyldiphenylsilylchloride (1.0 g, 3.6 mmol) was stirred for 10 h at room temperature and concentrated in vacuo to give a residue, which was partitioned between $CH_2Cl_2$ and $H_2O$. The organic layer was dried and concentrated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield **26E** (0.92 g, 60%) and **26T** (0.4 g, 26%).

*4.5.1.* ***26E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.07 (s, 9H), 2.99–3.05 (m, 1H), 3.64 (s, 3H), 3.71 (s, 3H), 3.76 (s, 3H), 3.98–4.01 (m, 1H), 4.11–4.14 (m, 1H), 4.30 (s, 1H), 5.06 (d, 1H, *J*=8.5 Hz), 6.34 (s, 1H), 6.48 and 6.61 (d, 2H, *J*=8.5 Hz), 6.69 (d, 2H, *J*=6.5 Hz), 7.04 (d, 2H, *J*=6.5 Hz), 7.35–7.42 (m, 6H), 7.61–7.65 (m, 4H); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.1, 26.8, 54.0, 55.1, 55.7, 67.8, 78.1, 110.6, 112.1, 113.2, 120.5, 127.8, 127.8, 129.9, 129.9, 131.8, 132.6, 135.1, 135.6, 135.6, 147.5, 148.3, 158.6; HRMS (ES) *m*/*z* 579.2541 (M+Na, $C_{34}H_{40}O_5SiNa$ requires 579.2543).

*4.5.2.* ***26T*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.02 (s, 9H), 3.00–3.02 (m, 1H), 3.68–3.73 (m, 1H), 3.72 (s, 3H), 3.78 (s, 3H), 3.83–3.86 (m, 1H), 3.86 (s, 3H), 5.18 (dd, 1H, *J*=3.5, 6.3 Hz), 6.66 (s, 1H), 6.74 and 6.77 (d, 2H, *J*=8 Hz), 6.80 (d, 2H, *J*=8.5 Hz), 7.15 (d, 2H, *J*=8.5 Hz), 7.27–7.38 (m, 6H), 7.46–7.50 (m, 4H); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.1, 26.8, 55.0, 55.2, 55.7, 55.8, 65.4, 74.3, 110.8, 112.6, 113.4, 121.3, 127.6, 127.8, 129.6, 129.6, 131.5, 133.0, 133.1, 134.4, 135.5, 135.5, 147.9, 148.5, 158.9; HRMS (ES) *m*/*z* 579.2543 (M+Na, $C_{34}H_{40}O_5SiNa$ requires 579.2543).

### 4.6. Diastereomeric 28E and 28T

To respective solutions of THF containing 1.0 M $LiAlH_4$ (8.8 mL, 8.8 mmol) were added mixture of **24E** and **24T** (3.7 g, 8.8 mmol) at room temperature. After stirring for 3 h, 15 mL $H_2O$ and 15 mL 1 N HCl solution at 0 °C were added and the solutions were extracted with $CH_2Cl_2$. The extracts were dried and concentrated in vacuo to afford mixture of **13E**/**13T**. A mixture solution of **13E**/**13T** (0.37 g, 1.0 mmol) in DMF 20 mL containing imidazole (0.17 g, 2.5 mmol) and *tert*-butyldiphenylsilylchloride (0.4 g, 1.5 mmol) was stirred for 10 h at room temperature and concentrated in vacuo to give a residue, which was partitioned between $CH_2Cl_2$ and $H_2O$. The organic layer was dried and concentrated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield **28E** (0.43 g, 70%) and **28T** (0.6 g, 10%).

*4.6.1.* ***28E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.08 (s, 9H), 2.95–2.99 (m, 1H), 3.66 (s, 3H), 3.69 (s, 6H), 3.76 (s, 3H), 3.78 (s, 3H), 4.00–4.03 (m, 1H), 4.11–4.15 (m, 1H), 4.33 (d, 1H, *J*=3 Hz), 5.06 (dd, 1H, *J*=3, 7.8 Hz), 6.35 (s, 2H), 6.41 (s, 1H), 6.53 (d, 1H, *J*=6.5 Hz), 6.65 (d, 1H, *J*=8 Hz), 7.34–7.43 (m, 6H), 7.59–7.64 (m, 4H); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.1, 26.8, 53.8, 55.8, 55.9, 60.8, 67.4, 78.4, 103.6, 110.8, 112.2, 120.7, 127.8, 129.9, 130.0, 131.7, 132.5, 135.6, 135.6, 136.8, 138.6, 147.8, 148.4, 152.6; HRMS (ES) *m*/*z* 639.2750 (M+Na, $C_{36}H_{44}O_7SiNa$ requires 639.2754).

*4.6.2.* ***28T*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.02 (s, 9H), 3.00–3.03 (m, 1H), 3.70–3.77 (m, 1H), 3.73 (s, 6H), 3.74 (s, 3H), 3.81 (s, 3H), 3.86 (s, 3H), 3.86–3.88 (m, 1H), 5.17 (dd, 1H, *J*=3.5, 6.5 Hz), 6.46 (s, 2H), 6.68 (s, 1H), 6.74 and 6.78 (d, 2H, *J*=8.5 Hz), 7.26–7.31 (m, 4H), 7.35–7.39 (m, 2H), 7.44 (d, 2H, *J*=6.5 Hz), 7.50 (d, 2H, *J*=7 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.1, 26.8, 29.6, 54.8, 55.7, 55.9, 60.8, 65.5, 75.0, 103.6, 110.8, 112.6, 121.3, 127.6, 129.6, 129.7, 131.3, 132.8, 133.0, 135.4, 137.1, 138.0, 148.0, 148.6, 152.9; HRMS (ES) *m*/*z* 693.2747 (M+Na, $C_{36}H_{44}O_7SiNa$ requires 639.2754).

### 4.7. Diastereomeric 10E and 10T

Each solution of **25** (5.95 g, 11.3 mmol for **25E**, 0.7 g, 1.35 mmol for **25T**) in THF (100 mL for **25E** and 30 mL for **25T**) containing tetrabutylammonium fluoride (1.0 M THF solution) (16.9 mL, 16.9 mmol for **25E**, 2 mL, 2 mmol for **25T**) was stirred for 4 h at room temperature and partitioned between $CH_2Cl_2$ and 1 N HCl. The organic layer of **25E** was dried and concentrated in vacuo to give a residue that was subjected to column chromatography (EtOAc/hexane 1:1) to yield **10E** (2.5 g, 77%). The organic layer of **25T** was dried and concentrated in vacuo to give a residue, which was washed with ether to yield **10T** (0.3 g, 80%).

*4.7.1.* ***10E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 3.00 (br s, 1H), 3.04–3.08 (m, 1H), 3.68 (s, 3H), 3.78 (s, 3H), 3.93–3.96 (m, 1H), 4.14–4.18 (m, 1H), 4.94 (d, 1H, *J*=9 Hz), 6.39 (s, 1H), 6.58 (d, 1H, *J*=8 Hz), 6.68 (d, 1H, *J*=8.5 Hz), 7.10–7.20 (m, 5H); $^{13}$C NMR ($CDCl_3$) $\delta$ 54.4, 55.7, 66.3,

79.6, 110.9, 112.0, 120.1, 126.5, 127.6, 128.1, 131.5, 142.8, 147.7, 148.5; HRMS (ES) *m/z* 311.1262 (M+Na, $C_{17}H_{20}O_4Na$ requires 311.1259).

*4.7.2.* ***10T*** *(sol mp 114 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 3.08–3.12 (m, 1H), 3.75–3.78 (m, 2H), 3.79 (s, 3H), 3.85 (s, 3H), 4.98 (dd, 1H, *J*=3, 7 Hz), 6.65 (s, 1H), 6.78–6.84 (m, 2H), 7.25–7.32 (m, 5H); $^{13}$C NMR ($CDCl_3$) $\delta$ 55.4, 55.8, 55.9, 64.1, 75.7, 111.3, 112.3, 120.9, 126.6, 127.9, 128.3, 130.5, 142.0, 148.3, 149.0; HRMS (ES) *m/z* 311.1261 (M+Na, $C_{17}H_{20}O_4Na$ requires 311.1259).

### 4.8. Diastereomeric 11E and 11T

Each solution of **26** (6.7 g, 12 mmol for **26E**, 2.64 g, 4.74 mmol for **26T**) in THF (120 mL for **26E** and 80 mL for **26T**) containing tetrabutylammonium fluoride (1.0 M THF solution) (18.1 mL, 18.1 mmol for **26E**, 7.1 mL, 7.1 mmol for **26T**) was stirred for 4 h at room temperature and partitioned between $CH_2Cl_2$ and 1 N HCl. Each organic layers were dried and concentrated in vacuo to give residues that were subjected to column chromatography (EtOAc/hexane 1:1) to yield **11E** (2.6 g, 69%) and **11T** (1.1 g, 75%).

*4.8.1.* ***11E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 2.85 (s, 1H), 2.95 (s, 1H), 3.03–3.07 (m, 1H), 3.70 (s, 3H), 3.72 (s, 3H), 3.78 (s, 3H), 3.91–3.94 (m, 1H), 4.14–4.17 (m, 1H), 4.90 (d, 1H, *J*=8.5 Hz), 6.40 (s, 1H), 6.56 (d, 1H, *J*=8 Hz), 6.67 (d, 1H, *J*=8.5 Hz), 6.71 (d, 2H, *J*=8.5 Hz), 7.04 (d, 2H, *J*=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 54.4, 55.2, 55.7, 66.5, 79.3, 110.9, 111.9, 113.5, 120.2, 127.7, 131.7, 135.0, 147.7, 148.5, 158.9; HRMS (ES) *m/z* 341.1355 (M+Na, $C_{18}H_{22}O_5Na$ requires 341.1365).

*4.8.2.* ***11T*** *(sol mp 116 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 1.64 (s, 1H), 2.19 (s, 1H), 3.03–3.07 (m, 1H), 3.66–3.71 (m, 2H), 3.77 (s, 3H), 3.80 (s, 3H), 3.84 (s, 3H), 4.89 (d, 1H, *J*=7 Hz), 6.66 (s, 1H), 6.76–6.84 (m, 4H), 7.16 (d, 2H, *J*=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 55.2, 55.3, 55.8, 55.8, 64.1, 75.4, 111.2, 112.2, 113.7, 120.8, 127.8, 130.8, 134.0, 148.2, 148.9, 159.2; HRMS (ES) *m/z* 341.1368 (M+Na, $C_{18}H_{22}O_5Na$ requires 341.1365).

### 4.9. Diastereomeric 13E and 13T

Each solution of **28** (1.0 g, 1.6 mmol for **28E** and **28T**) in THF (50 mL for **28E** and **28T**) containing tetrabutylammonium fluoride (1.0 M THF solution) (2.4 mL, 2.4 mmol for **28E** and **28T**) was stirred for 4 h at room temperature and partitioned between $CH_2Cl_2$ and 1 N HCl. Each organic layers were dried and concentrated in vacuo to give residues that were subjected to column chromatography (EtOAc/hexane 1:1) to yield **13E** (0.5 g, 83%) and **13T** (0.43 g, 71%).

*4.9.1.* ***13E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 2.80 (s, 1H), 2.99–3.03 (m, 1H), 3.08 (s, 1H), 3.67 (s, 6H), 3.72 (s, 3H), 3.75 (s, 3H), 3.79 (s, 3H), 3.93–3.97 (m, 1H), 4.15–4.19 (m, 1H), 4.88 (d, 1H, *J*=8.5 Hz), 6.30 (s, 2H), 6.45 (s, 1H), 6.59 (d, 1H, *J*=8.5 Hz), 6.70 (d, 1H, *J*=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 54.5, 55.8, 56.0, 60.8, 66.1, 79.6, 103.3, 111.1, 112.0, 120.3, 131.6, 137.1, 138.5, 147.9, 148.7, 152.8; HRMS (ES) *m/z* 401.1564 (M+Na, $C_{20}H_{26}O_7Na$ requires 401.1576).

*4.9.2.* ***13T*** *(sol mp 115 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 3.03–3.06 (m, 1H), 3.74–3.78 (m, 2H), 3.78 (s, 6H), 3.80 (s, 3H), 3.81 (s, 3H), 3.84 (s, 3H), 4.89 (dd, 1H, *J*=2.5, 7 Hz), 6.45 (s, 2H), 6.70 (s, 1H), 6.70–6.83 (m, 2H), 6.70 (d, 1H, *J*=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 55.3, 55.8, 56.0, 60.8, 64.1, 75.8, 103.5, 111.3, 112.3, 120.9, 130.6, 137.3, 137.6, 148.3, 149.0, 153.1; HRMS (ES) *m/z* 401.1573 (M+Na, $C_{20}H_{26}O_7Na$ requires 401.1576).

### 4.10. Diastereomeric 31E

A solution of diisopropylamine (8.9 mL, 62.6 mmol) in dry THF (90 mL) containing 25 mL (62.6 mmol) of 2.5 M *n*-BuLi at −78 °C and stirred for 30 min. Acetate ester **29** (10.3 g, 62.6 mmol) was added dropwise and the resulting solution was stirred over for 1 h followed by addition of veratrylaldehyde **18** (8.0 g, 48.1 mmol). After 3 h additional stirring at the same temperature, the mixture was diluted with $H_2O$ and extracted with EtOAc. The organic layer was dried and evaporated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield *erythro* **31E** (9.7 g, 61%) exclusively.

*4.10.1.* ***31E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.21 (t, 3H, *J*=7.5 Hz), 3.07 (s, 1H), 3.80 (s, 1H), 3.69 (s, 3H), 3.78 (s, 3H), 4.12–4.25 (m, 2H), 5.10 (d, 1H, *J*=9 Hz), 6.55 (s, 1H), 6.59–6.65 (m, 2H), 7.05–7.07 (m, 2H), 7.16–7.17 (m, 3H); $^{13}$C NMR ($CDCl_3$) $\delta$ 14.0, 55.6, 55.7, 60.2, 61.2, 76.4, 109.4, 110.4, 118.8, 127.4, 128.4, 128.5, 133.3, 135.4, 148.3, 148.4, 173.4; HRMS (ES) *m/z* 353.1371 (M+Na, $C_{19}H_{22}O_5Na$ requires 353.1365).

### 4.11. Diastereomeric 32E and 32T

A solution of diisopropylamine (8.9 mL, 62.6 mmol) in dry THF (90 mL) containing 25 mL (62.6 mmol) of 2.5 M *n*-BuLi at −78 °C and stirred for 30 min. Acetate ester **30** (12.2 g, 62.6 mmol) was added dropwise and the resulting solution was stirred over for 1 h followed by addition of veratrylaldehyde **18** (8.0 g, 48.1 mmol). After 3 h additional stirring at the same temperature, the mixture was diluted with $H_2O$ and extracted with EtOAc. The organic layer was dried and evaporated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield *erythro* **32E** (9.5 g, 55%) and **32T** (2.3 g, 13%).

*4.11.1.* ***32E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.21 (t, 3H, *J*=7 Hz), 3.03 (s, 1H) 3.71 (s, 3H), 3.72 (s, 3H), 3.73–3.75 (m, 1H), 3.78 (s, 3H), 4.11–4.23 (m, 2H), 5.06 (d, 1H, *J*=8 Hz), 6.58–6.65 (m, 3H), 6.69 (d, 2H, *J*=8.5 Hz), 6.97 (d, 2H, *J*=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 14.0, 55.1, 55.7, 55.7, 59.3, 61.1, 76.4, 109.4, 110.4, 113.8, 118.9, 127.5, 129.6, 131.0, 133.4, 148.3, 148.4, 158.8, 173.7; HRMS (ES) *m/z* 383.1458 (M+Na, $C_{20}H_{24}O_6Na$ requires 383.1471).

*4.11.2.* ***32T*** *(sol mp 132 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 1.06 (t, 3H, *J*=7 Hz), 3.72 (d, 1H, *J*=4.5 Hz), 3.78 (s, 6H), 3.85 (s, 3H), 3.92–4.05 (m, 2H), 5.18 (d, 1H, *J*=7.5 Hz), 6.74 (s, 1H), 6.78 (d, 1H, *J*=8 Hz), 6.84–6.86 (m, 3H), 7.25 (d, 2H, *J*=7.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 13.9, 55.2, 55.7, 55.8, 58.8, 60.8, 74.9, 109.7, 110.5, 113.9, 119.0, 126.7, 130.2, 133.4, 148.5, 148.5, 159.2, 172.7; HRMS (ES) *m/z* 383.1473 (M+Na, $C_{20}H_{24}O_6Na$ requires 383.1471).

### 4.12. Diastereomeric 14E

To solution of THF containing 1.0 M $LiAlH_4$ (6.4 mL, 6.4 mmol) was added **31E** (2.1 g, 6.4 mmol) at room temperature. After stirring for 3 h, 20 mL $H_2O$ and 20 mL 1 N HCl solution at 0 °C were added and the solutions were extracted with $CH_2Cl_2$. The extracts were dried and concentrated in vacuo to afford a residue, which was subjected to column chromatography (EtOAc/hexane 1:1) to yield **14E** (1.5 g, 83%).

*4.12.1.* ***14E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 3.05 (br s, 1H), 3.08–3.12 (m, 1H), 3.69 (s, 3H), 3.78 (s, 3H), 3.92–3.95 (m, 1H), 4.17–4.21 (m, 1H), 4.94 (d, 1H, *J*=9 Hz), 6.57 (s, 1H), 6.64 (s, 2H), 6.96 (d, 2H, *J*=7 Hz), 7.10–7.17 (m, 3H); $^{13}$C NMR ($CDCl_3$) $\delta$ 55.0, 55.7, 55.7, 66.5, 79.6, 109.5, 110.4, 118.7, 126.8, 128.4, 128.4, 135.3, 139.2, 148.2, 148.4; HRMS (ES) *m/z* 311.1250 (M+Na, $C_{17}H_{20}O_4Na$ requires 311.1259).

### 4.13. Diastereomeric 15E and 15T

To respective solutions of THF containing 1.0 M $LiAlH_4$ (22.0 mL, 22.0 mmol for **32E**, 4.0 mL, 4.0 mmol for **32T**) was added **32** (7.9 g,

22.0 mmol of **32E**, 1.5 g, 4.0 mmol of **32T**) at room temperature. After stirring for 3 h, 20 mL $H_2O$ and 20 mL 1 N HCl solution at 0 °C were added and the solutions were extracted with $CH_2Cl_2$. The extracts were dried and concentrated in vacuo to afford a residue, which was subjected to column chromatography (EtOAc/hexane 1:1) to yield **15E** (5.9 g, 84%) and **15T** (0.99 g, 77%).

*4.13.1.* ***15E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.55 (s, 1H), 2.78 (s, 1H), 3.06–3.10 (m, 1H), 3.71 (s, 3H), 3.74 (s, 3H), 3.80 (s, 3H), 3.91–3.94 (m, 1H), 4.16–4.20 (m, 1H), 4.92 (d, 1H, *J*=9 Hz), 6.63–6.71 (m, 3H), 6.70 (d, 2H, *J*=8.5 Hz), 6.90 (d, 2H, *J*=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 54.1, 55.1, 55.7, 66.6, 79.6, 109.5, 110.5, 113.8, 118.8, 129.4, 131.1, 135.4, 148.2, 148.5, 158.3; HRMS (ES) *m*/*z* 341.1355 (M+Na, $C_{18}H_{22}O_5Na$ requires 341.1365).

*4.13.2.* ***15T*** *(sol mp 132 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 2.14 (s, 1H), 3.04–3.08 (m, 1H), 3.71–3.75 (m, 2H), 3.77 (s, 6H), 3.85 (s, 3H), 4.89–4.91 (m, 1H), 6.71 (s, 1H), 6.79 (s, 2H), 6.85 (d, 2H, *J*=8.5 Hz), 7.14 (d, 2H, *J*=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 54.9, 55.2, 55.7, 55.8, 64.3, 75.7, 109.5, 110.6, 114.1, 118.9, 130.1, 130.3, 134.5, 148.5, 148.8, 158.9; HRMS (ES) *m*/*z* 341.1366 (M+Na, $C_{18}H_{22}O_5Na$ requires 341.1365).

### 4.14. Diastereomeric 42E and 43E/T

A solution of starting material (12.0 g, 42.0 mmol of **14E**, 1.2 g, 3.8 mmol of **15E**/**T**) in DMF (100 mL for **14E**, 40 mL for **15E**/**T**) containing imidazole (7.2 g, 105.2 mmol for **14E**, 0.8 g, 11.8 mmol for **15E**/**T**) and *tert*-butyldiphenylsilylchloride (15.0 g, 54.7 mmol for **14E**, 1.35 g, 4.9 mmol for **15E**/**T**) was stirred for 10 h at room temperature and concentrated in vacuo to give a residue, which was partitioned between $CH_2Cl_2$ and 1 N HCl. The organic layer was dried and concentrated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:3) to yield **42E** (13.5 g, 61%) and **43E**/**T** (1.26 g, 60%).

*4.14.1.* ***42E*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.08 (s, 9H), 3.07–3.11 (m, 1H), 3.69 (s, 3H), 3.71 (s, 3H), 3.79 (s, 3H), 3.95–3.98 (m, 1H), 4.11–4.15 (m, 1H), 4.42 (s, 1H), 5.06 (d, 1H, *J*=8 Hz), 6.59 (s, 1H), 6.63–6.69 (m, 2H), 6.90–6.91 (m, 2H), 7.08–7.10 (m, 3H), 7.35–7.44 (m, 6H), 7.61–7.66 (m, 4H); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.1, 26.8, 54.6, 55.6, 55.7, 67.8, 78.3, 109.9, 110.3, 118.9, 126.6, 127.6, 127.8, 128.1, 128.7, 129.9, 129.9, 132.5, 135.4, 135.6, 135.6, 139.1, 147.9, 148.2; HRMS (ES) *m*/*z* 549.2446 (M+Na, $C_{33}H_{38}O_4SiNa$ requires 549.2437).

*4.14.2.* ***43E/T*** *(3:1 diastereomeric mixture, l).* $^1$H NMR ($CDCl_3$) $\delta$ 1.08 (s, 9H), 3.00–3.4 (m, 1H), 3.69 (s, 3H), 3.78 (s, 3H), 4.00–4.03 (m, 1H), 4.16–4.20 (m, 1H), 4.42 (s, 1H), 5.11 (d, 1H, *J*=8 Hz), 6.61–6.66 (m, 5H), 6.79–6.81 (m, 3H), 7.35–7.38 (m, 5H), 7.61–7.66 (m, 4H); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.0, 26.8, 53.6, 55.0, 55.6, 55.6, 67.9, 78.3, 109.8, 110.3, 113.4, 119.0, 127.7, 129.6, 1303, 131.1, 132.5, 135.5, 135.5, 147.8, 148.2, 158.1; HRMS (ES) *m*/*z* 579.2543 (M+Na, $C_{34}H_{40}O_5SiNa$ requires 579.2543).

### 4.15. Synthesis of 44 and 45

A solution of pyridinium chlorochromate (1.1 g, 5.1 mmol for **42E**, 1.3 g, 5.9 mmol for **43E**) in $CH_2Cl_2$ 60 mL containing each starting material (1.8 g, 3.4 mmol of **42E**, 2.2 g, 4.0 mmol of **43E**) was stirred for 10 h at room temperature and partitioned between $CH_2Cl_2$ and $H_2O$. The organic layer was dried and concentrated in vacuo to give a residue, which was subjected to column chromatography (EtOAc/hexane 1:6) to yield **44** (0.86 g, 48%) and **45** (0.88 g, 40%).

*4.15.1.* ***44*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 0.94 (s, 9H), 3.88 (s, 3H), 3.89 (s, 3H), 3.89–3.92 (m, 1H), 4.42–4.46 (m, 1H), 4.75 (t, 1H, *J*=6.5 Hz), 6.80 (d, 1H, *J*=8.5 Hz), 7.19–7.21 (m, 1H), 7.23–7.26 (m, 4H), 7.30–7.31 (m, 2H), 7.34–7.40 (m, 4H), 7.47–7.51 (m, 3H), 7.55–7.57 (m, 1H), 7.63 (d, 2H, *J*=8 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.1, 26.7, 55.6, 55.9, 56.0, 66.3, 109.9, 110.7, 123.4, 127.2, 127.6, 127.6, 128.5, 128.7, 129.5, 129.6, 130.3, 133.4, 133.6, 135.6, 135.6, 137.0, 148.9, 153.1, 197.4; HRMS (ES) *m*/*z* 547.2281 (M+Na, $C_{33}H_{36}O_4SiNa$ requires 547.2281).

*4.15.2.* ***45*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 0.95 (s, 9H), 3.72 (s, 3H), 3.88 (s, 3H), 3.84–3.89 (m, 1H), 3.89 (s, 3H), 4.39–4.43 (m, 1H), 4.70 (t, 1H, *J*=6.5 Hz), 6.76–6.81 (m, 3H), 7.14 (d, 2H, *J*=8.5 Hz), 7.30–7.31 (m, 2H), 7.34–7.40 (m, 4H), 7.50 (d, 3H, *J*=6.5 Hz), 7.54 (d, 1H, *J*=8.5 Hz), 7.63 (d, 2H, *J*=6.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 19.1, 26.7, 54.7, 55.2, 55.9, 56.0, 66.4, 109.9, 110.7, 114.1, 123.3, 127.5, 127.6, 129.1, 129.5, 129.5, 129.6, 130.3, 133.5, 133.6, 135.6, 135.6, 148.9, 153.0, 158.8, 197.6; HRMS (ES) *m*/*z* 577.2374 (M+Na, $C_{34}H_{38}O_5SiNa$ requires 577.2386).

### 4.16. Synthesis of 40 and 41

A solution of each starting material (0.63 g, 1.2 mmol of **44**, 0.77 g, 1.3 mmol of **45**) in MeOH 30 mL containing concd HCl (3 mL) was stirred for 3 h at room temperature and partitioned between $CH_2Cl_2$ and $H_2O$. The organic layer was dried and concentrated in vacuo to give a residue that was subjected to column chromatography (EtOAc/hexane 1:2) to yield **40** (0.16 g, 47%) and **41** (0.19 g, 45%).

*4.16.1.* ***40*** *(sol mp 95 °C).* $^1$H NMR ($CDCl_3$) $\delta$ 3.85 (s, 3H), 3.86 (s, 3H), 3.84–3.87 (m, 1H), 4.22–4.26 (m, 1H), 4.71–4.74 (m, 1H), 6.76 (d, 1H, *J*=8.5 Hz), 7.02–7.31 (m, 5H), 7.50–7.54 (m, 2H); $^{13}$C NMR ($CDCl_3$) $\delta$ 55.8, 56.0, 56.0, 65.3, 110.0, 110.8, 123.9, 127.5, 128.3, 129.2, 129.3, 136.8, 148.8, 153.3, 198.5; HRMS (ES) *m*/*z* 309.1093 (M+Na, $C_{17}H_{18}O_4Na$ requires 309.1103).

*4.16.2.* ***41*** *(l).* $^1$H NMR ($CDCl_3$) $\delta$ 3.73 (s, 3H), 3.80–3.83 (m, 1H), 3.86 (s, 6H), 4.18–4.22 (m, 1H), 4.67–4.69 (m, 1H), 6.76 (d, 1H, *J*=8.5 Hz), 6.82 (d, 2H, *J*=8.5 Hz), 7.16 (d, 2H, *J*=8.5 Hz), 7.50 (s, 1H), 7.54 (d, 1H, *J*=8.5 Hz); $^{13}$C NMR ($CDCl_3$) $\delta$ 55.1, 55.2, 55.8, 56.0, 65.2, 109.9, 110.8, 114.6, 123.9, 128.7, 129.3, 148.8, 153.3, 158.9, 198.7; HRMS (ES) *m*/*z* 339.1212 (M+Na, $C_{18}H_{20}O_5Na$ requires 339.1208).

### 4.17. DCA-promoted photoreactions of dimeric lignin model compounds

Independent DCA saturated, $N_2$ or $O_2$ purged solutions, containing each dimeric lignin model compounds ($1.5\times10^{-5}$ mol, 2.1 mM) in 7 mL of 5% aqueous MeCN in quartz tubes were simultaneously irradiated by using uranium filtered light in a merry-go-round apparatus for 28 h (for $N_2$ purged solution) and 7 h (for $O_2$ purged solution). Each photolysates were subjected to HPLC analysis.

### 4.18. Relative quantum yields of DCA-promoted photoreactions of dimeric lignin model compounds

Independent DCA saturated, $N_2$ purged solutions containing each dimeric lignin model compounds ($1.5\times10^{-5}$ mol, 2.1 mM) in 7 mL of 5% aqueous MeCN in quartz tubes were simultaneously irradiated by using uranium filtered light in a merry-go-round apparatus for 6 h. Each photolysates were subjected to HPLC analysis.

### 4.19. DCA-fluorescence quenching of dimeric lignin model compounds

Fluorescence spectra were recorded on 2 mL of MeCN solutions of DCA ($5.4\times10^{-6}$ M) each containing 0, 0.25, 0.5, 1.0, 2.5 mM of the

respective dimeric lignin model compounds. The excitation wavelength was 400 nm.

### 4.20. Lignin peroxidase (LP) catalyzed reactions of dimeric lignin model compounds

To 200 μL of 0.1 M tartrate buffer (pH 3.4) were added 200 μL of dimeric lignin model compounds (1 mM dissolved in 17% MeCN–tartrate buffer, final concentration 0.4 mM) and 40 μL of lignin peroxidase (100.5 μM, final concentration 8 μM). After 60 μL of $H_2O_2$ (10 mM, final concentration 1.2 mM) was added, the solutions were agitated for 30 min and then subjected to HPLC analysis.

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## Supplementary data

$^1H$ and $^{13}C$ NMR spectra of all previously unidentified compounds and DCA-fluorescence quenching data. Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.tet.2015.04.077. These data include MOL files and InChiKeys of the most important compounds described in this article.

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