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Making natural products from renewable feedstocks: back to the roots?

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This review highlights the utilization of biomass-derived building blocks in the total synthesis of natural products. An overview over several renewable feedstock classes, namely wood/lignin, cellulose, chitin and chitosan, fats and oils, as well as terpenes, is given, covering the time span from the initial beginning of natural product synthesis until today. The focus is put on the origin of the employed carbon atoms and on the nature of the complex structures that were assembled therefrom. The emerging trend of turning away from petrochemically derived starting materials back to bio-based resources, just as seen in the early days of total synthesis, shall be demonstrated.

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1. Introduction

1.1. Total synthesis – a driving force for new developments

The synthesis of organic compounds of natural origin from simple starting materials – the so-called total synthesis – has attracted and fascinated chemists ever since the successful synthesis of “organic” urea from inorganic silver cyanate and ammonium chloride by Wöhler in 1828.¹ It should not be forgotten that the earlier isolation of pure morphine from opium by Sertürner in 1806² and his preparation of morphine salts in 1817³ were further defining moments in organic chemistry. Total synthesis has since emerged to be one of the most challenging and prestigious disciplines among the chemical sciences, as underlined by the Nobel prizes awarded to R. B. Woodward and E. J. Corey.

The fascination with this field arises from the diverse opportunities available in the application of natural products, combined with the possibility to provide these natural products independent of their natural source and to modify their structures at will.

Natural products have always served as an inspiration for the development of new pharmaceuticals, pesticides and herbicides or dyes – and total synthesis is often the only way to provide access to such products in sufficient quantities for extensive investigation, let alone commercial endeavours.^{4–6} Therefore, total synthesis, natural product isolation and structure elucidation have close ties. The search for new compounds with attractive biological activities or chemical structures has fueled the development of new analytical methods and synthetic chemists were never shy to tackle any attractive target molecule virtually regardless of its size. In contrast, the more challenging the target molecules were, the more effort was put into the development of new methods, technologies and theoretical concepts to make their preparation possible.^{7,8} This has made total synthesis an ideal proving ground for the utility of new synthetic developments. Furthermore, the *ab initio* synthesis

serves to verify or correct a proposed structure and the structures of numerous compounds had to be revised when total synthesis proved the originally proposed structure to be incorrect, often in terms of relative or absolute stereochemistry.^{9–20}

Working on total synthesis projects provides excellent training for synthetic chemists and is generally appreciated by future employers in the chemical and pharmaceutical sector because of the profound experience gained.²¹ The extensive and diverse challenges of organic synthesis provide a “feeling” for the reactivity of chemical compounds and profound knowledge on how to extract the literature to solve the numerous problems encountered on the way to the target. Although the number of total synthesis publications dwelling on the detours and problems encountered which contribute to the unmatched challenge of this discipline seems to be, unfortunately, declining, the successful pursuit of a total synthesis project is frequently associated with high skills in problem-solving and high levels of tolerance for frustration by the practitioner.²²

1.2. Requirements of eco-friendly synthesis

The increasing awareness of sustainability in our modern society has also led to reverberations in chemical research and industry which culminated in the Rio Declaration on Environment and Development from The United Nations Conference on Environment and Development in 1992.²³ Based on this declaration, Anastas and Warner have developed their twelve principles of green chemistry in 1998,²⁴ just as Anastas and Zimmermann phrased the related twelve principles of green engineering five years later.²⁵ Both catalogues are meant to be guidelines for the development of more eco-friendly syntheses, methodologies, technologies as well as processes and these are applicable to numerous facets of chemical research and production. However, the considerable potential of biocatalysis for “green” organic synthesis is not discussed therein. The present review will mainly focus on the use of renewable resources for the production of chemical building blocks and their value for organic synthesis. The reader shall also be referred to the rich body of existing literature providing more detailed information on the essence of green chemistry.^{26–52}

Furthermore, during the course of this paradigm shift in the world of chemistry, a number of terms and metrics to describe the extent of sustainability and “greenness” of certain reaction or process have been introduced.⁵³ The first metric that has been introduced is the Atom Economy concept of Trost, soon followed by the Environmental (E) factor of Sheldon. The former is defined as the ratio of the molecular mass of the desired product and the sum total of the molecular masses of all substances produced according to the stoichiometric equation.^{54,55} The latter, introduced in 1992, is the mass ratio of total waste and product and therefore indicates the efficiency and the environmental impact of a given process.^{56–58} These two and further metrics have been widely applied and discussed in detail elsewhere.^{59–61} Researchers of GlaxoSmithKline have recently developed the carbon efficiency, which is the percentage of carbon atoms remaining in the product relative to



all carbon atoms present in the entirety of reactants.^{62,63} Since organic synthesis is about constructing carbon skeletons, the origin and fate of carbon atoms significantly contributes to the sustainability of a certain organic product. Thus, the renewability of (starting) materials is a major aspect of green chemistry.

With few exceptions, chemical raw materials are currently produced from the fossil resources such as natural gas, coal and petroleum. Depletion of underground deposits, growing ecological risks associated with production as well as the carbon imbalance in the ecosphere resulting from the usage of these feedstocks makes them less favorable. Furthermore, the chemical diversity initially available from these sources is small and this has led to sometimes lengthy production processes but also to a rather limited primary product portfolio comprising alkanes, alkenes, alkynes and arenes. Any further functionalization such as the introduction of heteroatoms like oxygen, nitrogen, sulfur, phosphorus or halogens to generate advanced building blocks requires additional synthetic steps, often in the form of multistep cascades, which lead to additional waste production and energy consumption. In spite of these shortcomings, there was little incentive so far to change this traditional and irreversible chemical carbon flow.

In contrast, biomass-derived renewable starting materials often carry an appreciable degree of functionalization (heteroatoms, stereocenters) and can therefore represent useful advanced building blocks for synthesis. Because of their biogenetic relation or at least their structural proximity to nature-derived or -inspired target molecules, the step count required to convert them into suitable synthetic building blocks can be shorter than that available in the usage of their petrochemical counterparts. In addition to the renewability aspect and the option to close the carbon cycle, this is another advantage of bio-based starting materials. Here, we will mainly focus on the origin of the starting materials required to construct the carbon skeleton of natural products in order to illustrate their utility in total synthesis and organic synthesis of complex molecules in general.

Along with the utilization of biomass for fuel and energy production, the search for new sources of chemical feedstocks is a growing field in current chemical research. Numerous recent publications deal with the production of low molecular weight compounds from biomass and the valorization of these renewable feedstocks for synthetic purposes, although commodities such as adipic acid, acrylic acid or butanol currently still dominate the field.^{64–67}

1.3. Atom origin: historical developments

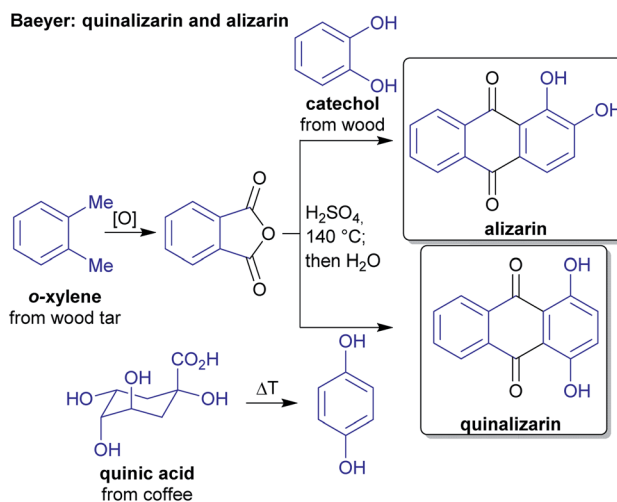
The concept of producing starting materials from natural resources is by no means new. In fact, before petroleum oil and coal deposits were discovered and exploited, the only available sources for pure organic compounds such as camphor, ethanol, methanol, hexadecanol, acetic acid, benzoic acid or benzaldehyde were microorganisms, plants and animals. Therefore, the young field of organic synthesis was initially restricted to these natural feedstocks and chemists have sought out to expand this

portfolio. Nevertheless, early-day chemists managed to synthesize natural products – some remarkable examples like von Baeyer's alizarin and quinalizarin⁶⁸ as well as indigo synthesis,^{69–71} Ladenburg's coniine synthesis^{72,73} or the synthesis of tyrian purple by Sachs and Sichel^{74–76} are depicted in Schemes 1–4.

During this period, industrial organic chemistry was intensely focused on the production of dyes and pigments and the demand was growing for synthetic approaches instead of reliance on natural sources of these products. Therefore, productive sources of raw materials were needed and the industrial production of petroleum oil and coal provided the required carbon sources. These petrochemicals were available in quantities sufficient to satisfy the needs of the expanding chemical industry. Synthetic routes and products were planned according to the starting materials available from those sources. A prime example is the manufacturing of indigo which was at first obtained from plant sources at an annual rate of 19 000 t in 1897 which dropped to 1000 t in 1914 as synthetic methods based on petrochemicals became available.⁷⁷ Around the same time, the industrial production of synthetic pharmaceuticals gained importance, *e.g.* the industrial scale production of acetylsalicylic acid⁷⁸ and of salvarsan,⁷⁹ which were both already produced from petrochemicals. The chemical industry developed to an important basis for economic growth in Western countries.

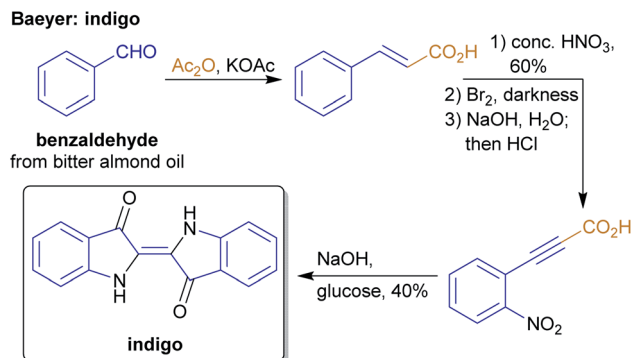
Despite the shift towards petrochemicals as new starting materials, biomass-derived feedstocks never were completely eliminated. The chiral pool, which is the collection of chiral terpenes, amino acids and carbohydrates and other chiral compounds available from nature,⁸⁰ was for many decades the only source of enantiopure catalysts and building blocks.⁸¹ The chiral pool was crucial for the synthesis of many natural products and other chiral nonracemic organic compounds.^{82–87}

The anthropogenic rise in atmospheric CO₂ levels casts shadows upon the continued extensive use of petrochemical

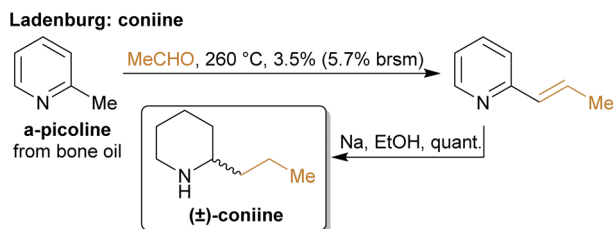
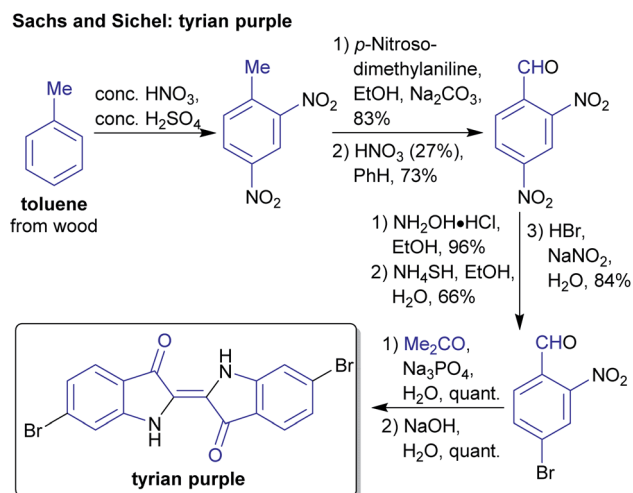


Scheme 1 Baeyer's alizarin and quinalizarin synthesis from phthalic anhydride and catechol/hydroquinone.



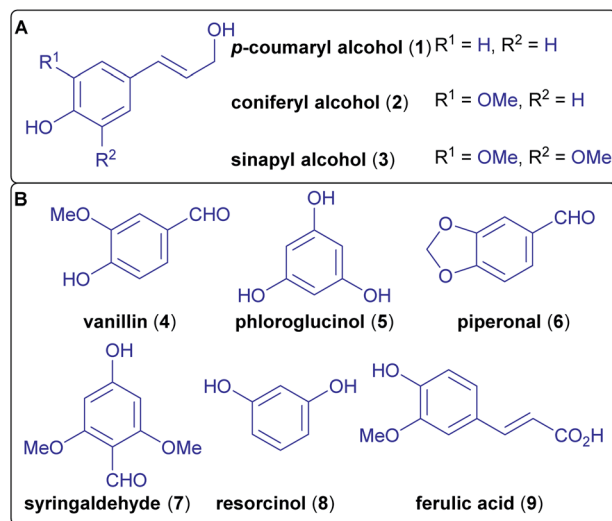


Scheme 2 Baeyer's indigo synthesis from cinnamic acid.

Scheme 3 Ladenburg's coniine synthesis from α -picoline.

Scheme 4 Sachs' and Sichel's synthesis of tyrian purple from xylochemical toluene.

resources.⁸⁸ With the largest fraction of fossil fuels being used for heating and/or cooling and transportation, the opinion that the use of fossil resources for chemistry will always be possible in future economic settings is still widespread. This is at least in part based on the assumption that mankind will acknowledge the overriding importance of synthetic chemistry and that this area will remain unaffected by any future changes in our carbon economy, hence making any adaption of feedstocks towards a higher sustainability obsolete. On the other hand, it is entirely possible that this belief will suffer the same fate as the presumption that chlorofluorocarbons or tetrachloromethane



Scheme 5 (A) Biosynthetic monomers of lignin. (B) Several wood-derived compounds used in natural product synthesis.

will always be available at a reasonable price for laboratory-scale applications or that the number of chemicals available from commercial suppliers cannot ever decrease. It thus makes sense that researchers are now reviving the use of natural feedstocks in organic synthesis which had moved in the background more than a century ago. Although outstanding achievements have already been made in the valorization of biomass as a chemical feedstock, the full substitution of petrochemicals is still a distant dream.

2. Natural product syntheses using renewable feedstocks

The main intention of the present review is the appreciation of syntheses that were performed based on renewable carbon sources and that follow some of the concepts of sustainable chemistry. The potential of those approaches is highlighted to provide inspiration to fellow researchers. In contrast to the synthesis of polymers^{89–91} or other functional materials,^{92–96} the concept of total synthesis using renewable carbon sources is not widespread. Total synthesis is already operating under very stringent conditions and the way of accomplishing the ultimate goal is often subordinated, with the application of any suitable method and effort being justified, at least in an academic setting. To compare several functioning approaches to the same target molecule, aspects like step count and overall yield are commonly applied, yet softer or less well-defined aspects such as “elegance” also play a role.

The following syntheses demonstrate that the challenge of avoiding fossil resources can be tackled at the same time. The key criterion for the inclusion of total syntheses in this review is the origin of carbon atoms and the renewability of the starting materials used. Other aspects of sustainable chemistry such as the use of benign solvents, of catalytic methods instead of stoichiometric transformations, the avoidance of protecting



groups and critical reagents or the step efficiency will be addressed and discussed where relevant. Furthermore, we primarily selected examples where starting materials were used in a so-called “class-transcendent” fashion (*i.e.* the product belongs to a different class of compounds than the starting material) to demonstrate the full potential of the starting materials and the capability of combining different sources. We pay tribute to the fact that a synthesis of a saccharide from a terpene is more challenging and remarkable than a synthesis from another saccharide. In fact, (oligo)peptide, (oligo)saccharide and (oligo)nucleotide natural products will not be covered, as the transcendence criterion is not fulfilled in these cases and the natural origin of the starting materials is rather obvious. For a better visualization, we use a color coding for the carbon atoms of each moiety derived from the respective biomass resources presented herein.

Wood- (or lignin-) derived carbons are colored in blue, (hemi)cellulose-as well as carbohydrate-based moieties are shown in green, compounds obtainable from fats and oils are colored in orange, purple was chosen for chitin- and chitosan-derived groups, and terpene and terpenoids are shown in red.

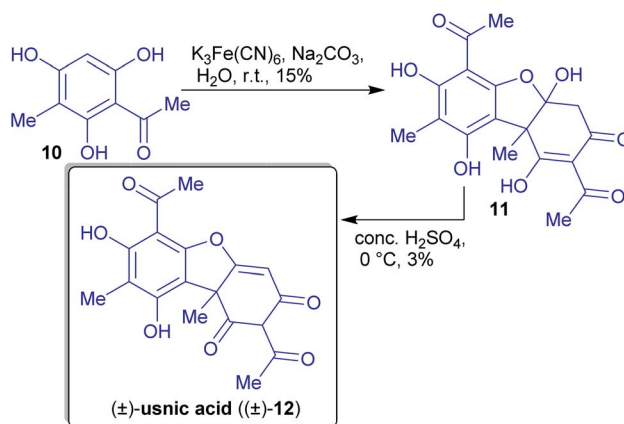
Heteroatoms are also colored in this code if they are introduced from the respective bio-based material. Otherwise, inserted heteroatoms will be black. These five classes of renewable starting materials were selected as they represent the most intensely investigated and used sources for starting materials to date. Starting materials of natural origin not covered by the above list specified in this review (*e.g.* amino acids) are also colored black. Petrochemistry-derived carbon atoms that remain in the final product will not occur in this review, but for the sake of simplicity, carbons of this kind introduced transiently will also be depicted in black.

2.1. Wood/lignin

A major component of lignocellulose is lignin, the largest source of aromatics on earth, as wood-derived biomass consists of up to 35% of lignin.⁹⁷ Lignin is an amorphous cross-linked biopolymer that, in combination with cellulose and hemicelluloses, confers structural stability to plants.⁹⁸ The complexity of its structure and its chemical stability make this biopolymer difficult to break down into useful building blocks.^{99,100} Nevertheless, the benefits of its use would be its carbon-neutrality and the lack of competition with food production (not considering the competition for potentially arable land).¹⁰¹ Therefore, it is a promising alternative to petroleum resources.^{102,103} Lignin can be derived from wood pulp and is a waste product of paper production. It is biosynthetically derived from three phenylpropanoid monolignol monomers, differing only in their oxygenation pattern (Scheme 5).

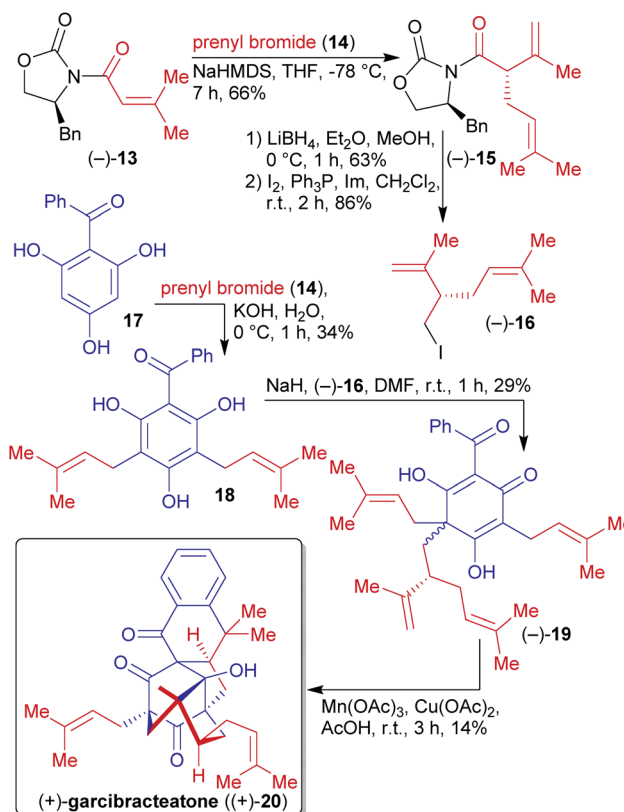
2.1.1. Valorization of wood/lignin. Various approaches for lignin depolymerization have been developed (oxidative, reductive, pyrolysis, hydrogenolysis, deoxygenation)^{99,104–108} and these can deliver several platform chemicals such as vanillin (**4**) which proved useful for the synthesis of natural products (Scheme 5).^{109,110}

More advanced strategies for lignin valorization are the focus of ongoing research and promise to convert wood-derived



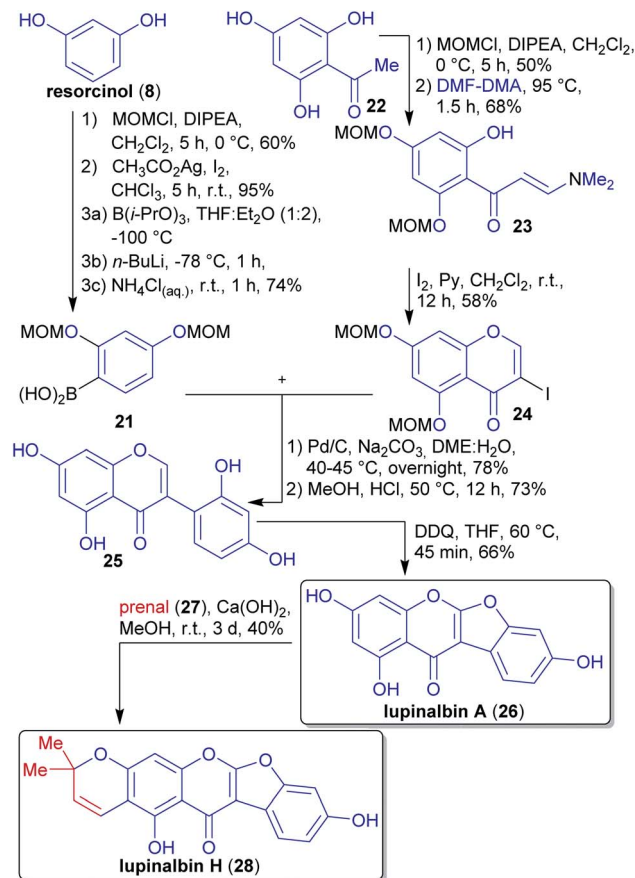
Scheme 6 Synthesis of (±)-usnic acid ((±)-12) via oxidative coupling of acetophenone moieties **10**.

industrial waste or residues from agriculture into carbon-neutral, renewable building blocks. However, numerous issues such as lignin repolymerisation, low overall efficiency, structural variability and problems with product separation and purification need to be addressed.¹⁰⁰ The reader may be referred to further references on utilizing wood or lignin as the source of platform chemicals and their acquisition.^{99,100,108,111–113} Arduengo and Opatz have coined the term “xylochemistry” for the synthesis of organic compound exclusively from wood-derived building blocks (*vide infra*).^{110,114–116}



Scheme 7 Enantioselective synthesis of (+)-garcibracteatone ((+)-20) mimicking biosynthesis.





Scheme 8 Synthesis of lupinalbin H (28) from fragments 21 and 24 via Suzuki–Miyaura coupling.

2.1.2. Natural product syntheses using wood/lignin derived starting materials

2.1.2.1. (\pm)-Usnic acid. Barton *et al.* published a two-step synthesis of (\pm)-usnic acid ((\pm)-12) by oxidative coupling of acetylated phloroglucinol **10** using potassium ferricyanide and subsequent acid-catalyzed dehydration (Scheme 6). Acetophenone **10** can be synthesized in two steps from natural phloroglucinol (**5**)¹¹⁷ through Vilsmeier–Haack reaction followed by aldehyde reduction and subsequent acetylation with acetic anhydride.^{118,119}

An advantage of this synthesis is the use of the environmentally benign solvents. Ferricyanide is a green oxidant and no carbon atom is “lost” during the synthesis (high atom economy). The reported yields are unfortunately low.

2.1.2.2. (+)-Garcibracteateone. George *et al.* reported the first enantioselective synthesis of the non-natural (+)-garcibracteateone ((+)-20) in 2014, which also allowed the determination of the absolute configuration of the naturally occurring enantiomer (Scheme 7).^{120,121} Benzoylphloroglucinol (**17**) can be derived from natural phloroglucinol (**5**) and benzoic acid *via* Friedel–Crafts acylation.^{117,122–125} Phloroglucinol derivative **17** was first reacted with prenyl bromide (**14**), accessible from the natural product prenenol, and subsequent C-alkylation with iodide (–)-16 affording the dearomatized phloroglucinol

19.^{126–128} Oxidative radical cyclization completed the synthesis of (+)-garcibracteateone ((+)-20).

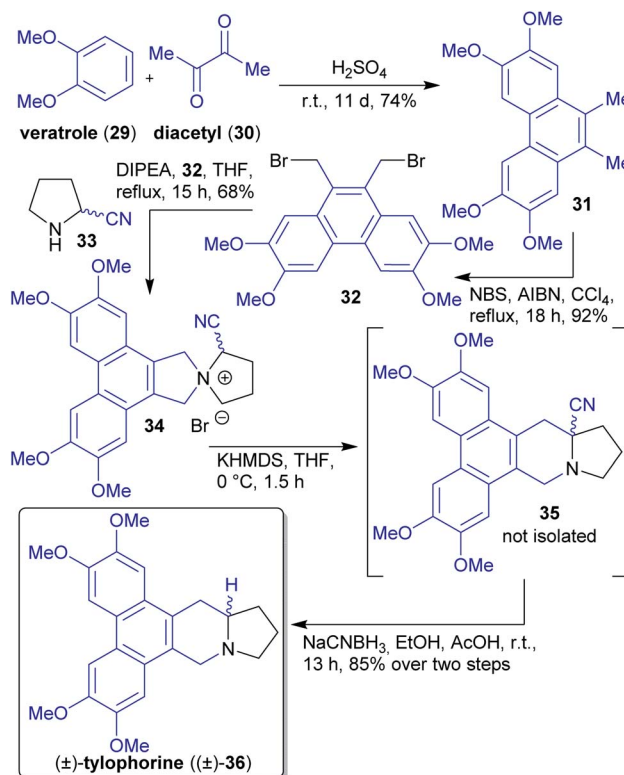
N-Acylloxazolidinone **13** could be prepared from biomass-derived 3-methylcrotonic acid¹²⁹ and the phenylalanine-derived Evans auxiliary.¹³⁰ Subsequent α -alkylation with prenyl bromide (**14**) and reduction followed by iodination delivered the enantioenriched fragment (–)-16.

The avoidance of protecting groups and the construction of a complex molecular scaffold from simple starting materials in a short route are the highlights of this sequence.

2.1.2.3. Lupinalbin H. The flavonoid lupinalbin H (**28**) was first isolated by Tahara *et al.* from the methanolic extract of the roots of yellow lupin (*Lupinus luteus* cv Topaz).¹³¹ Its first synthesis in 2011 by van Heerden *et al.* used a Suzuki–Miyaura reaction, followed by an oxidative cyclohydrogenation and a final 6 π -electrocyclization (Scheme 8).¹³²

Boronic acid **21** was prepared from resorcinol (**8**), which can be isolated from various plant species.^{133–135} The hydroxy groups were protected and the arene regioselectively iodinated at C-5 to select the site of borylation.

The synthesis of fragment **24** was reported in 2010 by the same group starting from trihydroxyacetophenone **22**.¹³⁶ The isolation of the latter from plants has been reported.^{137,138} Reaction with DMF-dimethyl acetal, theoretically accessible from the wood-derived renewables DMF¹³⁹ and (MeO)₂SO₂ (prepared by reaction of MeOH with SO₃),¹⁴⁰ and subsequent iodination led to fragment **24**.¹⁴¹

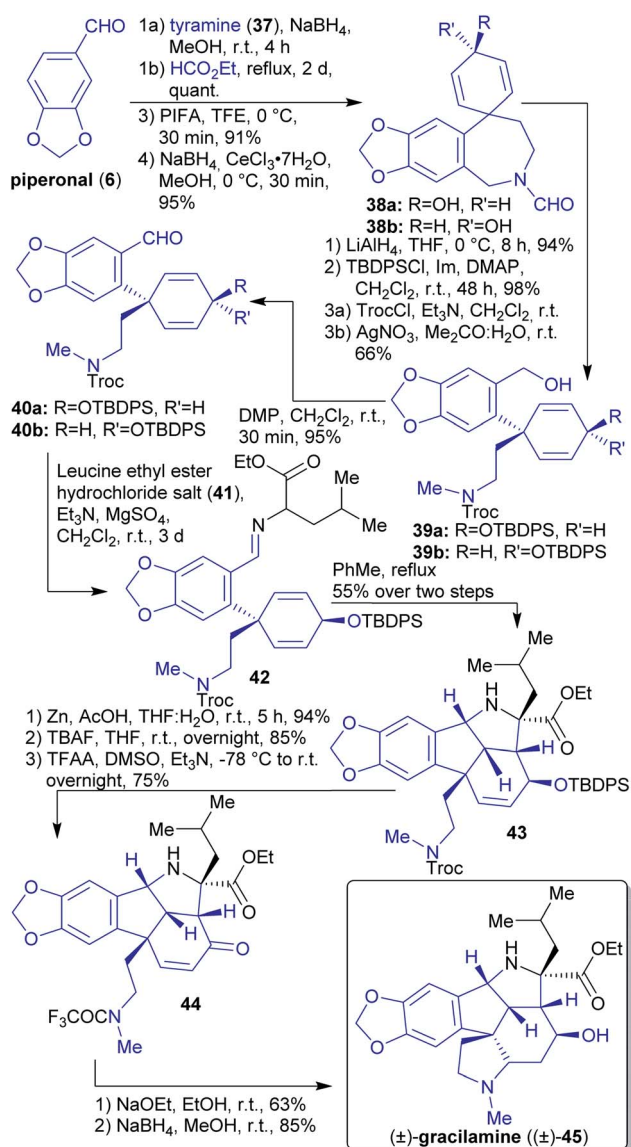


Scheme 9 Synthesis of (\pm)-tylophorine ((\pm)-36) following xylochemical principles.



By coupling of both precursors in the presence of a palladium catalyst, isoflavone **25** was obtained, and after deprotection, oxidation furnished lupinalbin A (**26**). This naturally-occurring phytoestrogen was condensed with prenal (**27**) (accessible *via* catalytic aerobic oxidation of prenil)^{128,142} to complete the synthesis of **28**.¹⁴³ The authors were able to formally derive all carbon- and heteroatoms from renewable sources. The choice of solvents and reagents (*e.g.* DDQ) was however traditional and less compatible with the principles of green chemistry.

2.1.2.4. (\pm)-Tylophorine. Opatz *et al.* reported a short synthesis of the phenanthroindolizine alkaloid (\pm)-tylophorine ((\pm)-**36**)¹⁴⁴ with a Stevens rearrangement as the key step and devoid of any protecting group manipulations (Scheme 9).¹⁴⁵ Three of five overall steps can be performed in a one-pot procedure and no chromatographic purification was required, which is in accordance with “green” principles of pollution prevention.²⁴



Scheme 10 Synthesis of (\pm)-gracilamine ((\pm)-**45**) from piperonal (**6**).

Starting materials veratrole (**29**) and diacetyl (**30**) can be obtained from biomass^{146,147} and were subjected to an acid catalyzed reaction furnishing phenanthrene derivative **31**, which was brominated under free radical conditions. Reaction with α -amino nitrile **33** afforded spirocyclic compound **34**, which underwent a Stevens rearrangement to furnish natural (\pm)-tylophorine ((\pm)-**36**) after reduction with NaCNBH₃.¹⁴⁵

The α -amino nitrile **33** was synthesized from pyrrolidine and sodium cyanide, the former can be derived from proline *e.g. via* a Pd-catalyzed decarboxylation reaction.^{145,148}

Drawbacks of the route are the use of toxic solvents and reagents, which are to be avoided according to “green” principles. It should be noted that natural tylophorine is almost racemic.¹⁴⁹

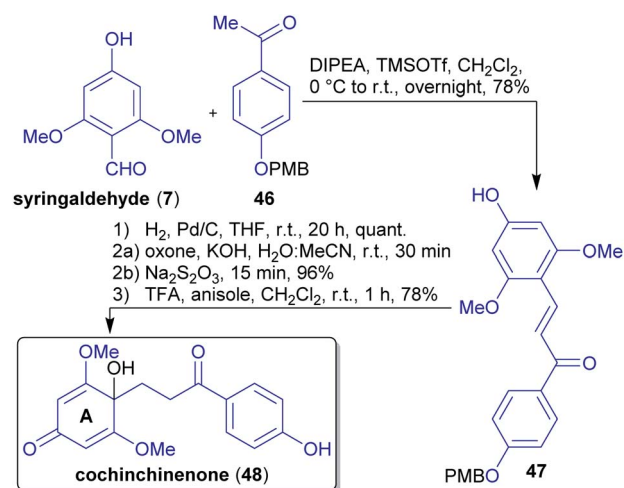
2.1.2.5. (\pm)-Gracilamine. The natural product (\pm)-gracilamine ((\pm)-**45**) was isolated in 2005¹⁵⁰ and its first synthesis was reported in 2012 by Ma *et al.*¹⁵¹

The key step in the formation of spirocyclic intermediates **38a** and **38b** was an intramolecular oxidative phenol coupling (Scheme 10).¹⁵² The starting materials for this reaction, piperonal (**6**) and tyramine (**37**), can be obtained from renewable sources.^{153–155} Reduction of spirocyclic compound **38a** and **38b** with LiAlH₄ followed by protection with TBDPSCI, ring opening using TrocCl gave benzyl alcohols **39a** and **39b** after treating with AgNO₃ in the presence of H₂O.

Alcohols **39a** and **39b** were oxidized to aldehydes **40a** and **40b**. Through the condensation reaction of aldehyde **40a** and leucine ethyl ester (**41**), imine **42** was formed, which reacted in a [3 + 2]-cycloaddition with the corresponding azomethine ylide under formation of the natural product scaffold **43** containing all of the carbon atoms required. The final product **45** was obtained by deprotection, cyclization and reduction using NaBH₄.¹⁵¹

In this synthesis, all carbon- and hetero atoms can be obtained from renewable sources.

2.1.2.6. Cochinchinenone. The first total synthesis of the natural product cochinchinenone (**48**)¹⁵⁶ in only five steps and 58% overall yield was reported from Carreño *et al.*¹⁵⁷ The synthesis



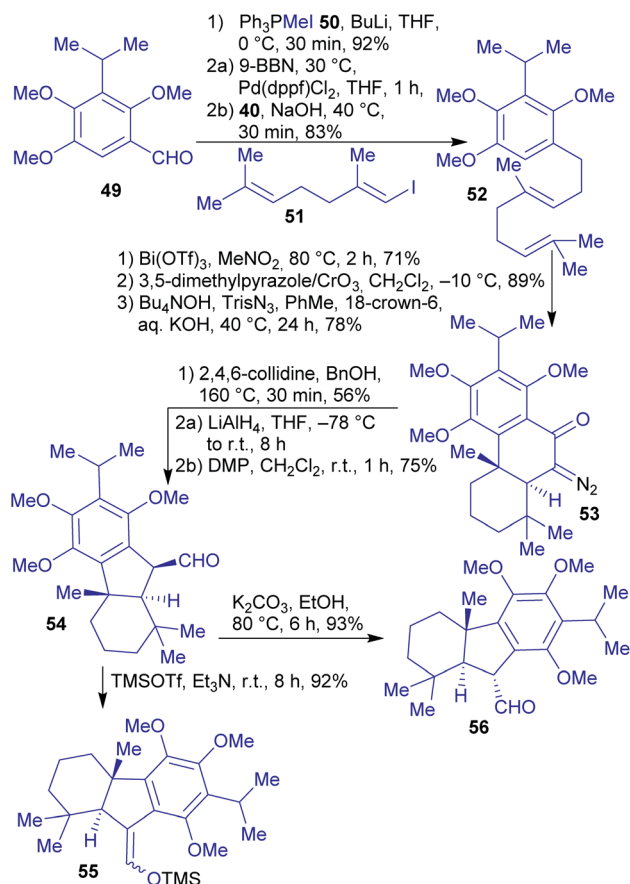
Scheme 11 Concise and first synthesis of cochinchinenone (**48**) based on lignin derived starting materials.



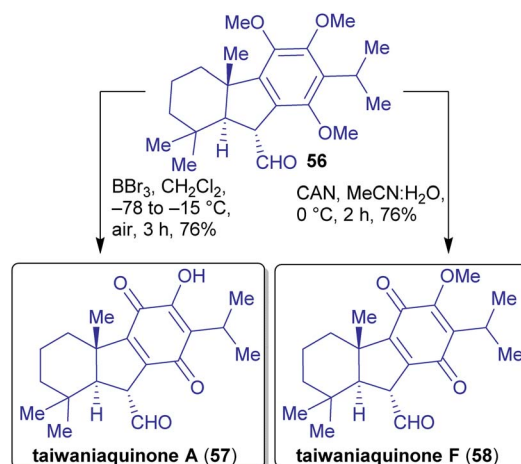
commenced with the Mukaiyama aldol condensation of syringaldehyde (7) with PMB-protected 4-hydroxy-acetophenone (46), both derivable from lignin (Scheme 11).^{158,159} To obtain chalcone 48 with a *p*-quinol moiety in ring A, the corresponding ketone 47 was dearomatized oxidatively. To this end, the choice of the right protective group was crucial since derivatives such as OMOM, OTBDMS, OTBDPS, OTHP, and OBN led to negative results during the synthesis. Furthermore, the dearomatization did not proceed with a free OH-group because of a competing Baeyer–Villiger reaction taking place instead.¹⁵⁷ Only a single protective group is required and there is no loss of carbon atoms throughout the synthesis.

2.1.2.7. *Taiwaniaquinones and taiwaniaquinols.* The total synthesis of the racemic taiwaniaquinoids was reported by Li *et al.* in 2013.¹⁶⁰

The synthesis commenced with the preparation of common intermediate 54 with a *trans* A/B ring junction on a gram scale (Scheme 12). 1,2,4-Trimethoxybenzene is available from renewable resources and can be transformed into benzaldehyde 49 in several steps.^{161,162} This was then subjected to a Wittig olefination, followed by a Pd-catalyzed Suzuki–Miyaura coupling with iododiene 51 to afford diene 52. Through a Bi(OTf)₃-catalyzed cationic cyclization and a Wolff-type ring contraction as the key steps, intermediate 54 was obtained. From there on, the natural products taiwaniaquinones A (57)



Scheme 12 Synthesis of intermediate 54 and subsequent intermediates for the synthesis of taiwaniaquinones and taiwaniaquinols, accessible via a Wolff-type ring contraction.



Scheme 13 Closing synthesis of taiwaniaquinone A (57) and F (58).

and F (58), and taiwaniaquinols B (59) and D (60) were prepared in 2–3 steps in racemic form.¹⁶⁰

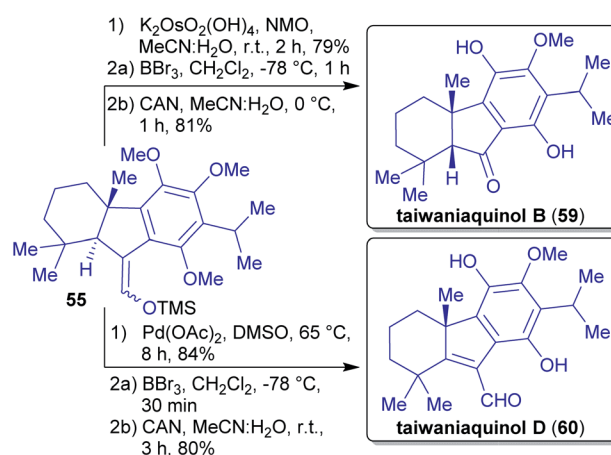
Quinones A 57 and F 58 were accessed by epimerization of aldehyde 54 followed by oxidation (taiwaniaquinone F (58)) or by oxidation and *O*-demethylation (taiwaniaquinone A (57), Scheme 13).

Quinols B 59 and D 60 were obtained from the silyl enol ether derived from intermediate 54. Via a sequence of Saegusa–Ito oxidation, demethylation and oxidation, quinol D 60 was furnished. Subjecting the silyl enol ether of 54 to dihydroxylation, a demethylation and an oxidation reaction led to quinol B 59 (Scheme 14).

All four natural products synthesized occur in the same plant species.¹⁶³

Methylenetriphenylphosphorane (50) was prepared from triphenylphosphine and iodomethane,¹⁶⁴ available from methanol (wood spirit) and HI.¹⁶⁵

Iododiene 51 can be prepared in three steps from 6-methylhept-5-en-2-one, which can be isolated from several plant species.^{166,167}



Scheme 14 Closing synthesis of taiwaniaquinol B (59) and D (60).



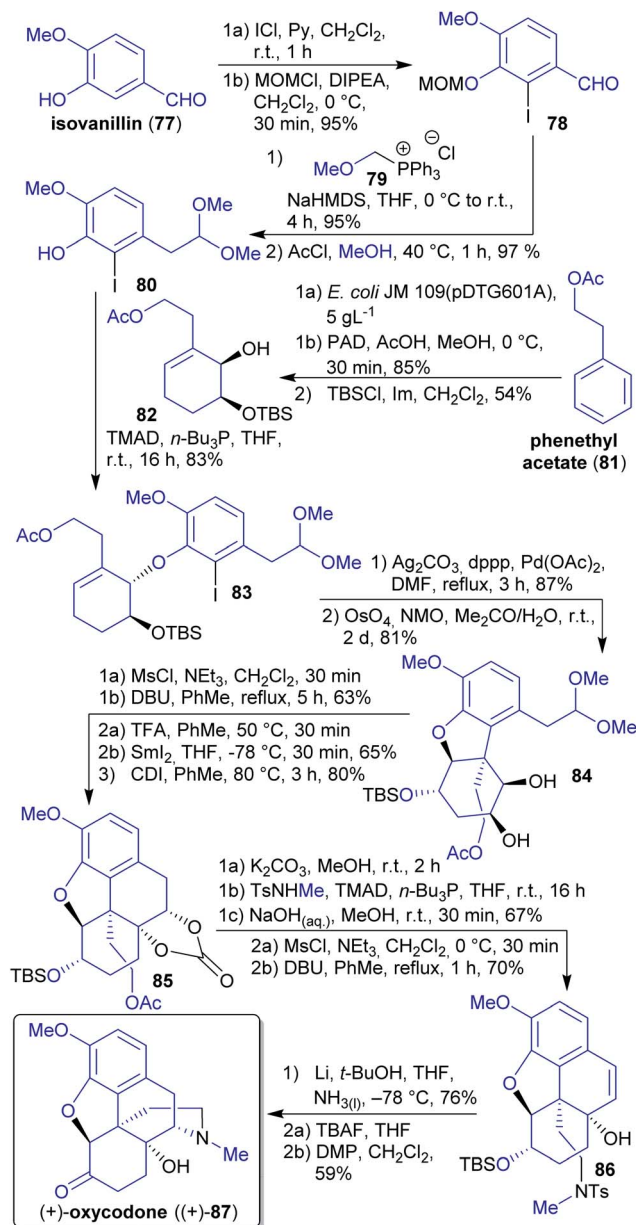
compound **72**.¹⁶⁹ This was reacted with lithiated dithiane **73**, followed by reduction and deprotection to furnish triol **74**.

2-Propyl-1,3-dithiane (**73**) is accessible *via* a condensation between potentially renewable butyraldehyde (1-butanol is a common fermentation product),¹⁷⁰ and 1,3-propanedithiol.¹⁷¹ The synthesis was concluded by a Lewis acid-mediated cyclization reaction, followed by an oxa-Pictet–Spengler reaction, Jones oxidation and chelate-controlled regioselective *O*-demethylation affording the natural product (+)-monocerin ((+)-**76**).¹⁷²

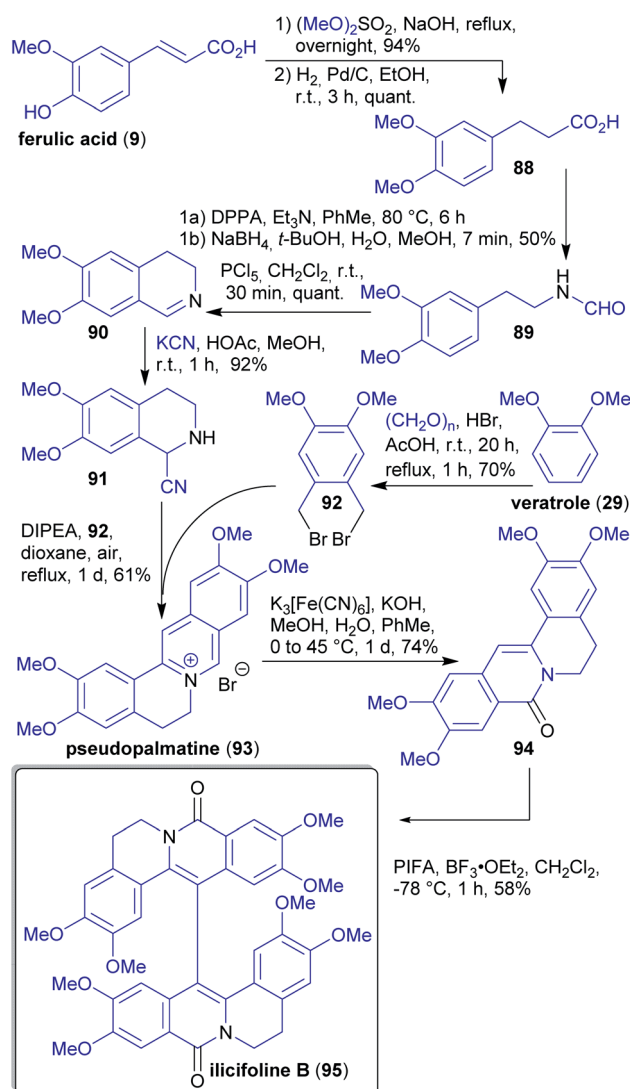
3,4,5-Trimethoxybenzaldehyde (**61**) is accessible from a renewable source.¹⁷³ Vinylmagnesium bromide (**71**) can be synthesized in two steps from acrylic acid,^{174–176} derivable from lactic acid.^{177–181} Reaction of sodium methanolate with CHCl_3 in the presence of DMF leads to trimethyl orthoformate.¹⁸² The

required chloroform can *e.g.* be prepared by chlorination of biogenic methane or *via* reaction of methanol with FeCl_3 but its general avoidance would be desirable.¹⁸³ Considering “green” chemistry, particularly the use of toxic reagents (Jones reagent, HF/HMPA , BCl_3) appears problematic.

2.1.2.10. (+)-Oxycodone. In 2019, Hudlicky *et al.* reported a synthesis of (+)-oxycodone ((+)-**87**), the non-natural enantiomer of this opioid.¹⁸⁹ Its natural antipode¹⁹⁰ is widely applied in pain management.¹⁹¹ The synthesis commenced with the microbial dihydroxylation of phenethyl acetate (**81**) (available through fermentation of corn, barley and sweet molasses),¹⁹² selective hydrogenation of the less hindered $\text{C}=\text{C}$ -double bond and a Mitsunobu reaction with iodophenol **80** (Scheme 17). The latter compound can be derived from natural isovanillin (**77**) *via* iodination,¹⁹³ Wittig olefination with (methoxymethyl)triphenylphosphonium chloride (**79**) and reaction with methanolic HCl .¹⁹⁴ Wittig salt **79** is theoretically accessible from the reaction of formaldehyde with MeOH and HCl , affording

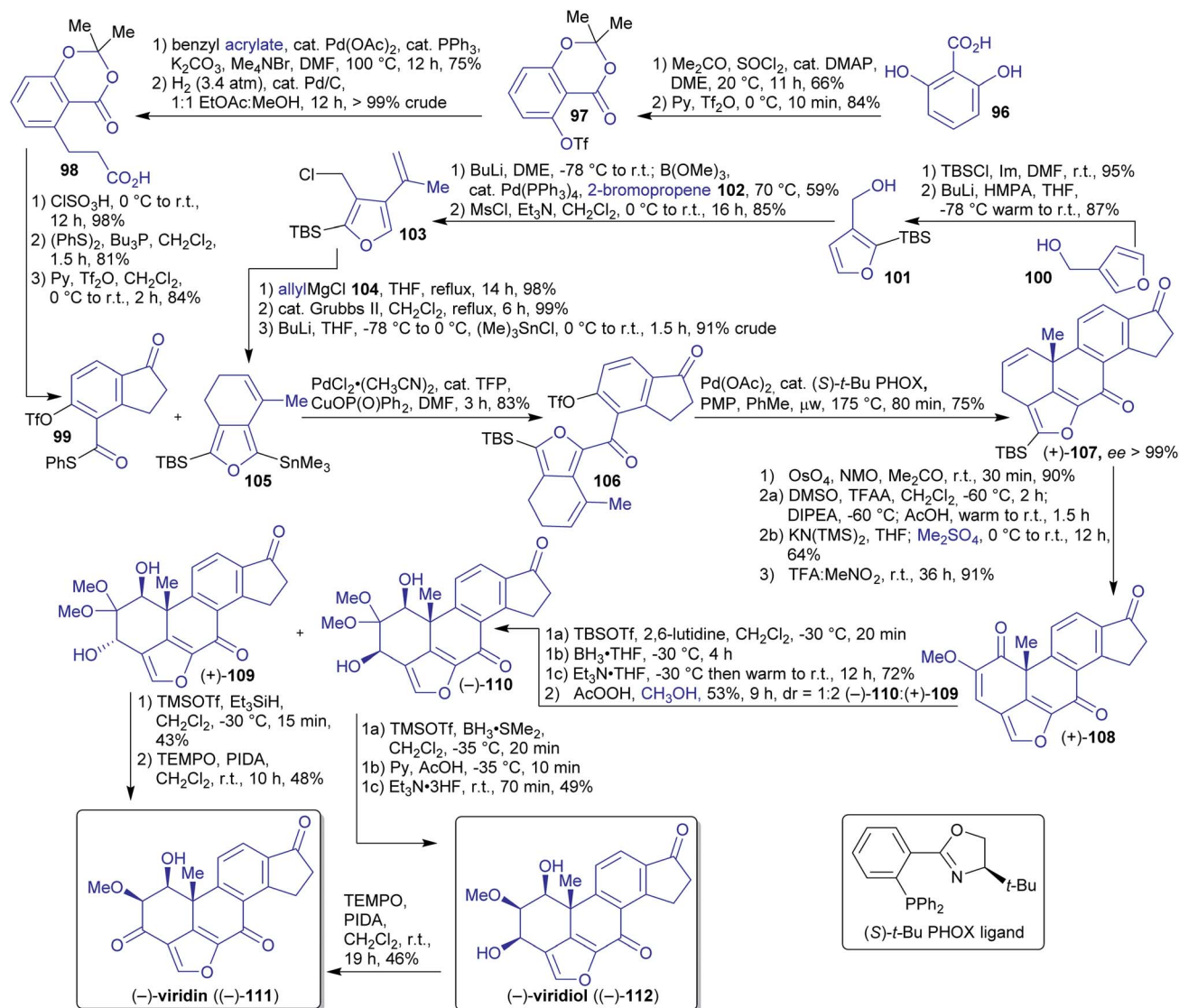


Scheme 17 Synthesis of (+)-oxycodone ((+)-**87**) from phenethyl acetate (**81**) and isovanillin (**77**). PAD = potassium azodicarboxylate.



Scheme 18 Synthesis of ilicifoline B (**95**) from wood derived starting materials **9** and **29**.





Scheme 19 First enantioselective synthesis of (-)-viridin ((-)-111) and (-)-viridiol ((-)-112).

chloromethyl methyl ether,¹⁹⁵ and subsequent reaction with PPh₃.¹⁹⁶ Intramolecular Heck reaction of ether **83** followed by dihydroxylation furnished diol **84**. Through mesylation and DBU-catalyzed elimination, a ketone was obtained. Subsequent pinacol-type coupling with deprotected aldehyde and protection yielded carbonate **85**. Methanolysis of the acetate followed by Mitsunobu coupling, carbonate hydrolysis and two-step dehydration led to tosylamide **86**. The synthesis was completed *via* Parker radical amination and oxidation of deprotected alcohol yielding (+)-oxycodone ((+)-**87**).¹⁸⁹ Tosylmethylamine can be prepared from methanol and tosylamide¹⁹⁷ (product of toluene-derived TsCl with sodium cyanate or ammonia).^{198,199}

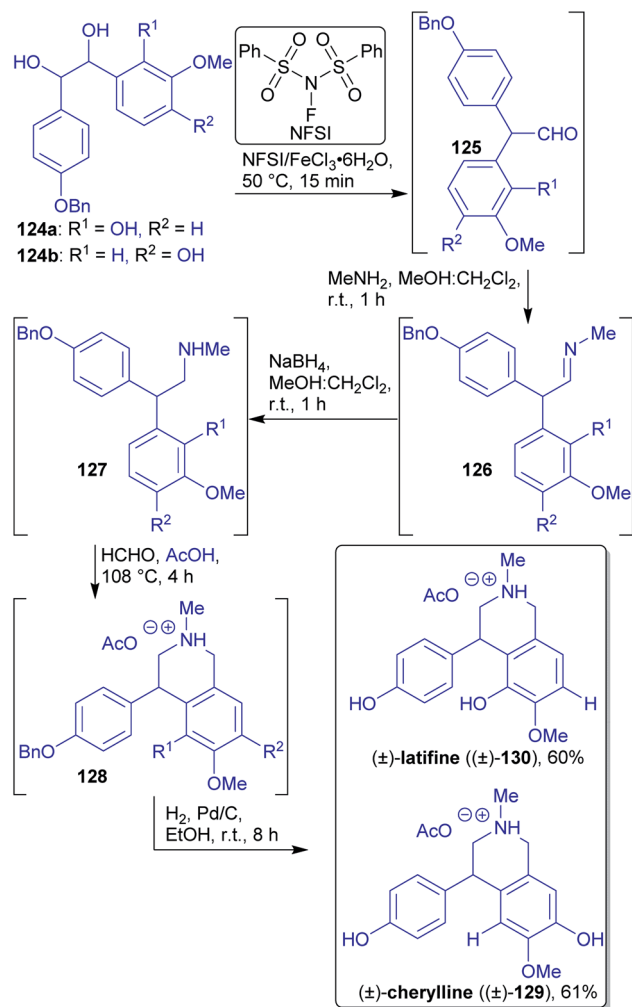
The authors could have derived all carbon atoms in the product from renewable resources. The use of a highly stereoselective microbial dihydroxylation and of several “green” solvents (MeOH, Me₂CO, H₂O) are an advantage, yet toxic reagents and the use of non-green protecting groups had to be included.

2.1.2.11. *Ilicifoline* B. Opatz *et al.* reported the first total synthesis of the dimeric protoberberine-type alkaloid ilicifoline B (**95**) in 2015.¹¹⁴

The synthesis of **95**²⁰⁰ commenced with methylation and hydrogenation of the wood-derivable natural product ferulic acid (**9**),²⁰¹ followed by a Bischler–Napieralski cyclization and addition of *in situ* generated HCN²⁰² to furnish α -amino nitrile **91** (Scheme 18). In a cascade reaction with dibromide **92**, berberine alkaloid pseudopalmatine (**93**) is formed, subsequent oxidation and dimerization furnished alkaloid ilicifoline B (**95**).¹¹⁴ Dibromide **92** is accessible from veratrole (**29**), a pyrolysis product of wood.²⁰³ Formaldehyde and dimethyl sulfate can be obtained from methanol.^{140,204}

The authors used entirely wood-derivable building blocks, so-called xylochemicals, instead of conventional petrochemicals for the construction of the natural product carbon scaffold. In the light of “green” chemistry, the use of a non-toxic cyanide source and solvents like toluene, MeOH, H₂O or EtOH is





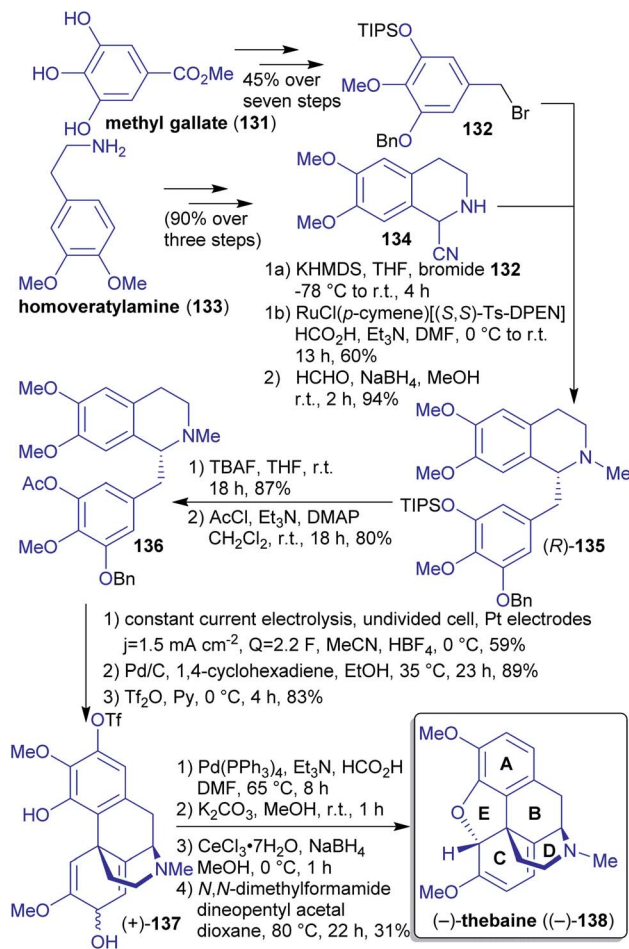
Scheme 20 One-pot synthesis of (±)-latifine ((±)-130) and (±)-cherylline ((±)-129) utilizing a catalyzed, solvent free pinacol rearrangement.

positive, yet undesired solvents like dioxane, CH₂Cl₂ should generally be avoided.

2.1.2.12. (–)-Viridin and (–)-viridiol. In 2017, Guerrero *et al.* reported the first enantioselective synthesis of the natural products (–)-viridin ((–)-111) and (–)-viridiol ((–)-112).^{205–207}

The authors pursued the convergent approach of coupling two achiral fragments and employing an enantioselective intramolecular Heck reaction to set the absolute stereochemical configuration of an all-carbon quaternary stereocenter in the synthesis of 111 and 112.^{205–207} Indanone 99 was synthesized starting from plant-derivable 2,6-dihydroxybenzoic acid (96)²⁰⁸ by protection of all hydroxy groups,^{209,210} Heck alkenylation and subsequent hydrogenation furnishing dihydrocinnamic acid 98 (Scheme 19). This intermediate is converted into indanone 99 in three steps.

The starting material 3-hydroxymethylfuran (100) for the synthesis of the second fragment can be obtained by reduction of naturally occurring 3-furoic acid.^{211,212} Subsequent silylation, reaction with 2-bromopropene (102) and chlorination led to compound 103. 2-Bromopropene (87) is accessible from wood-



Scheme 21 Synthesis of (–)-thebaine ((–)-138) from renewable starting materials.

derived acetone²¹³ in two steps *via* reaction with hydrazine and subsequent bromination.^{214,215} Compound 103 was reacted with allylmagnesium chloride 104, followed by ring closing metathesis and stannylation reaction affording second fragment 105. Allylmagnesium chloride (104) can be obtained from allylic alcohol (available from biomass)^{216,217} *via* chlorination and reaction with magnesium.^{218,219}

Enantiopure compound (+)-107 already bears the complete carbon skeleton of viridin (111) and was obtained from fragments 99 and 105 *via* Liebeskind coupling and Heck cyclization. Upjohn dihydroxylation, double Swern oxidation and *O*-methylation yielded methoxy enone 108. Site- and diastereoselective reduction followed by treatment with AcOOH and MeOH delivered a mixture of hydroxy ketal diastereomers (+)-109 and (–)-110.

Reduction of ketal (+)-109 with Et₃SiH and TEMPO-catalyzed oxidation led to viridin (–)-111. Alternatively, ketal (–)-110 was reduced with dimethyl borane to afford natural product viridiol (–)-112 and *via* same oxidative conditions as before viridin (–)-111.

Unfortunately, numerous highly toxic or otherwise problematic reagents had to be used (*e.g.* HMPA, OsO₄, TFA, TFAA).



2.1.2.13. (\pm)-*Latifine* and (\pm)-*cherylline*. The hydrobenzoin substrates **124a** and **124b** were synthesized *via* a Wittig epoxidation/ring-opening one-pot protocol from substituted benzaldehydes accessible from biomass.^{109,201,220,221} The authors prepared 2,2-diarylacetaldehyde **125a** and **125b** *via* a pinacol rearrangement using an eco-friendly catalyst and microwave irradiation under solvent-free conditions (Scheme 20). This key step was followed by one-pot reductive amination, Pictet-Spengler and hydrogenation reactions and only one chromatographic purification to afford the desired isoquinoline alkaloids **129** and **130**.²²⁰ (\pm)-*Cherylline* (**129**) and (\pm)-*latifine* (**130**) are both secondary metabolites of *Crinum latifolium* L (Amaryllidaceae).²²²

The authors provided an efficient and solvent-economical route in which half of the reactions operate at ambient temperature so that no additional heating is required. In general, one-pot approach are also favorable in the light of “green” chemistry.

2.1.2.14. ($-$)-*Thebaine*. So far, all synthetic approaches towards ($-$)-thebaine (($-$)-**138**) using stoichiometric oxidants to mimic the biosynthetic oxidative phenol coupling delivered only low yields. The group of Opatz *et al.* reported the first electrochemical access to natural ($-$)-thebaine (($-$)-**138**) *via* regio- and diastereoselective anodic coupling (Scheme 22).^{223,224}

Homoveratrylamine (**133**) and methyl gallate (**131**) are both accessible from biomass^{225,226} and were reacted in several steps to furnish compounds **134** and **132**. *Via* a deprotonation/alkylation/reduction sequence, tetrahydroisoquinoline **135** was formed. The anodic coupling was performed after a less favorable but inevitable switch of protecting groups, yielding intermediate **137**. Subsequent deacetylation, Luche reduction and closure of the E-ring through conjugate nucleophilic substitution afforded ($-$)-thebaine (($-$)-**138**).

Based on this procedure, the authors were also able to synthesize the natural opioid ($-$)-oxycodone (($-$)-**87**), whereas

the synthesis of its optical antipode was achieved by Hudlicky *et al.* along a different synthetic route (*vide supra*).^{189,227}

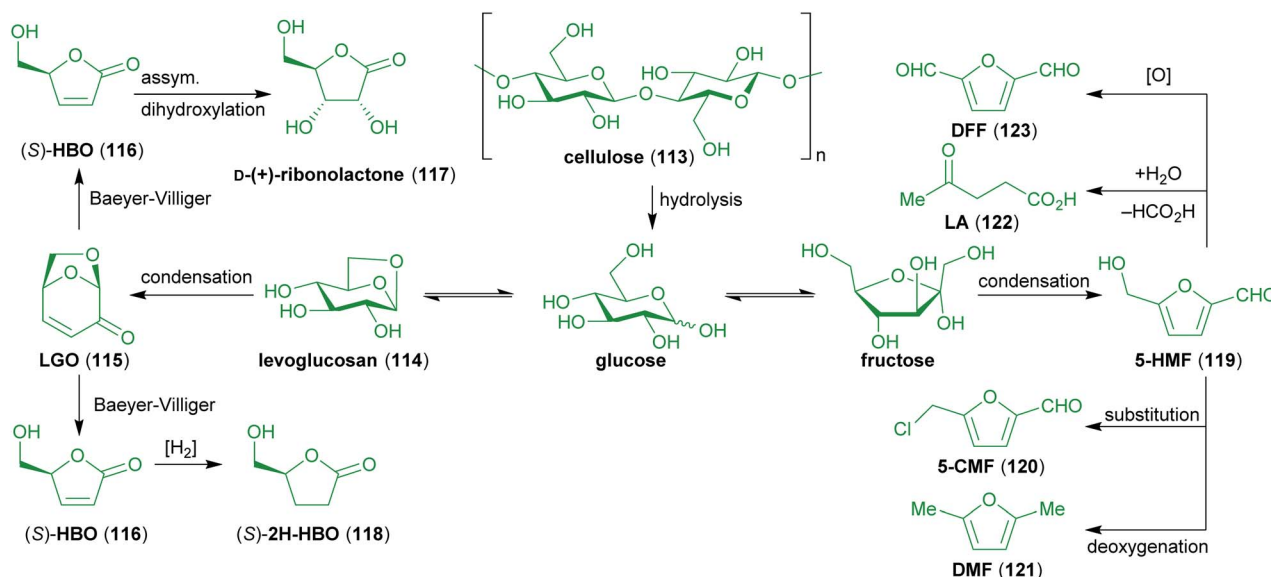
Under “green” aspects, switching of protecting groups is not ideal. Furthermore, several of undesired solvents (DMF, THF, CH₂Cl₂) as well as toxic or hazardous reagents (1,4-cyclohexadiene, DMAP, HCO₂H, Et₃N) had to be used.

2.2. Cellulose

Cellulose (**113**) and hemicelluloses account for up to 80% of the dry biomass of plants in which they form the cell walls. While the chemical structures of hemicelluloses are very heterogeneous, cellulose consists exclusively of $\beta(1 \rightarrow 4)$ linked poly-D-glucose, making it a non-edible carbohydrate source for most animals including humans. It is a very abundant and promising sustainable feedstock for chemical raw materials.

2.2.1. **Valorization of cellulose.** In view of the large body of research regarding the valorization of cellulose and considering the amount of literature and reviews available, we restricted the presented chemical starting materials to the molecules relevant for the syntheses covered in this review (Scheme 21). For detailed information on the utilization of cellulose for fuel^{228–230} and chemical raw material production^{231–233} as well as for macromolecular chemistry,²²⁸ we refer the reader to the references given.

One of the most important small molecules obtainable from cellulose (as well as of hexoses in general) in high yields is 5-hydroxymethylfurfural (5-HMF, **119**)^{234–236} and related compounds that can either be obtained from 5-HMF (**119**) or directly from cellulose. Those are 5-(chloromethyl)furfural (5-CMF, **120**),^{237,238} 2,5-diformylfuran (DFF, **123**),^{239,240} 2,5-dimethylfuran (DMF, **121**, not to be confused with dimethylformamide commonly abbreviated in the same way)^{241,242} and levulinic acid (LA, **122**).^{243–246} Another interesting raw material is levoglucosenone (LGO, **115**), which bears several useful



Scheme 22 Valorization of cellulose for selected platform chemicals.



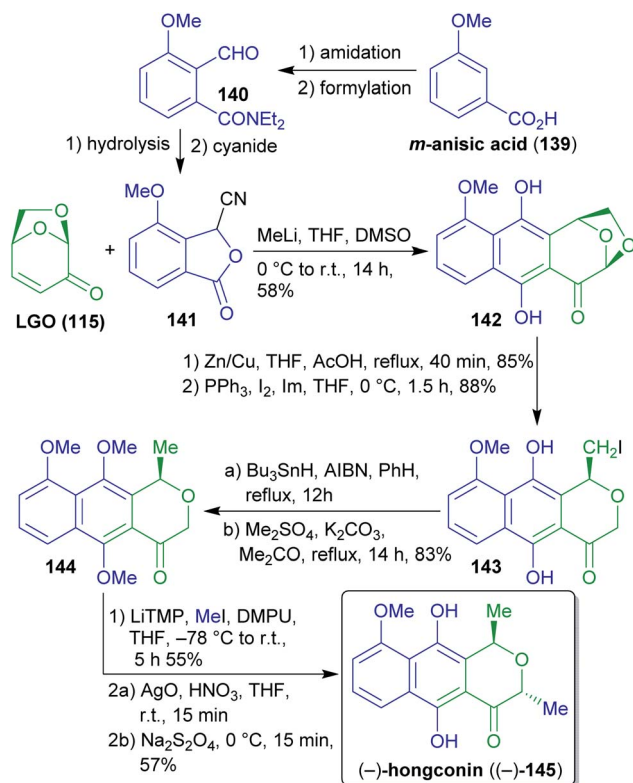
functional groups in the form of an enone and an acetal moiety in its chiral bicyclic skeleton.^{247–250} It is derived from levoglucosan (**114**), a product of the pyrolysis of cellulose.^{251–253} Furthermore, it can be transformed to other useful compounds like (*S*)- γ -hydroxymethyl- α,β -butenolide (HBO, **116**) via Baeyer–Villiger oxidation,^{254,255} the respective saturated derivative (2H-HBO, **118**),²⁵⁵ and *D*-(+)-ribono-1,4-lactone (**117**).²⁵⁶

Although glucose is an important compound obtainable from cellulose that has elaborately been used for the natural product synthesis, those syntheses are only cursory covered in this review due to the wealth of literature already available.^{257–262}

2.2.2. Natural product syntheses using cellulose derived starting materials

2.2.2.1. (–)-Hongconin. The cardioprotective agent hongconin ((–)-**145**)^{263–265} was synthesized from (–)-levoglucosone ((–)-**115**) via Hauser–Kraus-annulation with cyanophthalide **141** by Swenton *et al.* (Scheme 23).²⁶⁶ The latter can be synthesized from the xylochemical 3-methoxybenzoic acid (**139**).²⁶⁷ Acetal reduction, Appel reaction, radical reduction and methylation furnished naphthopyran **144**. Deprotonation and treatment with iodomethane in the presence of DMPU (avoiding the more common but highly toxic and carcinogenic HMPA) gave a 4 : 1-mixture in favor of the desired *trans*-product which was converted to the respective quinone with AgO and subsequently treated with sodium dithionite to obtain (–)-hongconin ((–)-**145**).

This very straightforward approach provides access to enantiopure (–)-hongconin (**145**) in a short sequence utilizing



Scheme 23 Synthesis of (–)-hongconin ((–)-**145**) from levoglucosone (**115**).

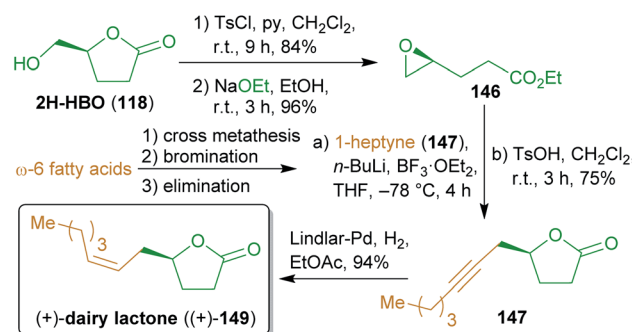
cellulose-derived **115** as a chiral synthon and wood-derived **139** as an aromatic building block. Although the procedures used are based on less green methods, only one protecting group transformation had to be performed.

2.2.2.2. (+)-Dairy lactone. A concise synthesis of the flavoring compound dairy lactone (**149**), named after its natural occurrence in cow milk as well as its dairy-like odor and flavor,^{268,269} was presented in 2016 using the levoglucosone-derived γ -lactone 2H-HBO (**118**).²⁷⁰ To create an electrophilic species from alcohol **118**, it was converted to epoxide **146** via the respective tosylate and alkaline transesterification (Scheme 24). Reaction with lithiated 1-heptyne (**147**) and acidic transesterification furnished lactone **148**, which was hydrogenated to (+)-**149** using a Lindlar catalyst. Alkyne **147** can be produced from any ω -6 fatty acid derivative (*e.g.* linoleic acid) by cross metathesis with ethylene,²⁷¹ bromination and dehydrobromination.²⁷²

2.2.2.3. (+)-Herbarumins. Another levoglucosone-derived starting material, δ -ribonolactone (**117**), was used as its acetonide protected derivative **150** by Fürstner *et al.*²⁷³ for the synthesis of phytotoxic herbarumins I and II (**158** and **159**, Scheme 25).²⁷⁴ Similar to the synthesis of **149**, the lactone was converted to an epoxide through ring transformation, which was then transformed into lactol **152** by nucleophilic attack of ethylmagnesium bromide and reduction. The hemiacetal was subjected to a Steglich esterification with hexenoic acids **155a–b** to furnish **156a–b**. 5-Hexenoic acid (**155a**) as well as the 2-methoxymethyl derivative **155b**, which was synthesized from **155a** using Evans aldol methodology, are available from eicos-5-enoic acid (**153**) via cross metathesis with ethylene.²⁷⁵ Esters **156a–b** were subjected to olefin metathesis using catalyst **157** to ensure *E*-selectivity. Final deprotection furnished enantiopure (+)-**158** and (+)-**159**.

Although the solvents used during these syntheses are ecologically less favorable, the number of protecting group manipulations is minimal and makes this route a straightforward approach to two natural products from bio-based starting materials.

2.2.2.4. (–)-Jiadifenolide. Jiadifenolide (**168**), a neurotrophic sesquiterpenoid,^{284,285} was synthesized by Theodorakis *et al.*²⁸⁶ from cyclopentadienone (**161**) which is available from methyl levulinate (**160**) in a single step (Scheme 26).²⁸⁷ Allylation with



Scheme 24 Synthesis of (+)-dairy lactone ((+)-**149**) from 2H-HBO (**118**).



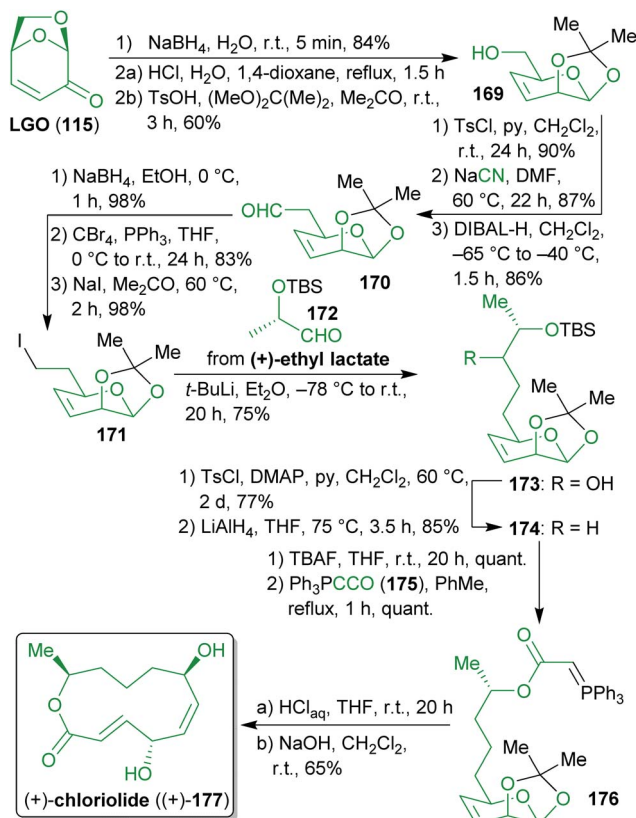
alcohol and oxidation of the secondary alcohol restored the carbonyl group, which was converted to the respective vinyl triflate to perform carbomethoxylation. After desilylation, spontaneous lactonization occurred to form **165**, which was oxidized to the respective epoxide. Oxidative cleavage of the terminal olefin and oxidation of the resulting aldehyde triggered “6-*exo-tet*” epoxide opening to form the desired lactone **166** after TBS-deprotection. For this sequence, a direct Ru^{III}-based oxidation of the terminal alkene to the carboxylic acid was investigated but was unsuccessful and led to decomposition. Therefore, the more circumstantial two-step sequence had to be used. Directed epoxidation and direct treatment of the acidic solution with DMP led to the α,β -unsaturated ketone, acid-catalyzed epoxide opening and transesterification to the thermodynamically favored 5-membered lactone. After hydrogenation of the double bond and TES protection, intermediate **167** was obtained. Next, the remaining carbonyl group should be transformed into a methyl group. This seemingly simple transformation proved challenging and the conventional methylenation approaches (Wittig reaction, Ti- and Zn-based) failed. Therefore, the vinyl triflate was prepared with Comins' reagent and Pd⁰-catalyzed cross coupling with AlMe₃ (accessible from Al and iodomethane)²⁹⁵ gave the desired product. A final three-step one-pot sequence of hydrogenation, hydroxylation *via* the enolate and oxaziridine **154** as well as Jones oxidation gave (–)-jiadifenolide ((–)-**168**) in 1.5% overall yield over 25

steps, representing the first total synthesis of this natural product.

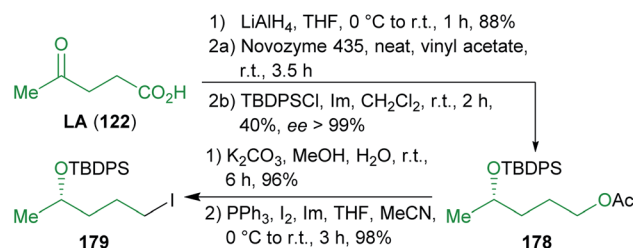
The foregoing synthesis is an excellent example of constructing a fairly complex and stereochemically demanding natural product from simple and bio-derivable building blocks. Inevitable detours had to be taken, which unfortunately decreased the eco-friendliness of the approach, yet the entire carbon backbone was constructed from renewable starting materials.

2.2.2.5. (+)-Chloriolide. In 2014, Schobert *et al.* synthesized the fungal 12-membered macrolide chloriolide (**177**)²⁷⁶ from levoglucosenone (**115**) and (+)-lactic acid *via* a Wittig-type macrocyclization (Scheme 27).²⁷⁷ Starting from **115**, ketone reduction, acetal hydrolysis and acetonide protection led to alcohol **169**, which was converted to the C₁-homologated aldehyde **170** *via* transformation into a leaving group, nucleophilic substitution with cyanide and reduction. Sodium cyanide is currently produced by the Andrussow process from methane and ammonia and subsequent reaction with lye.^{278,279} Considering that synthetic natural gas and methane derived from agricultural waste and manure are widely established concepts,²⁸⁰ even methane-derived NaCN could be produced on the basis of renewables. Another route to biomass-based HCN has been mentioned earlier.²⁸¹ The cumulated ylide **175** which is prepared from the respective alkoxy carbonyl-methylenephosphorane and therefore from an α -haloacetic acid derivative^{282,283} was used to synthesize ylide ester **176** after TBS deprotection. Acetonide cleavage and Wittig-cyclization gave enantiopure (+)-**177**. The presented work makes use of simple chiral bio-based starting materials to build a fairly complex natural product.

2.2.2.6. (–)-Aspergillides. For a formal synthesis of the cytotoxic aspergillides A and B (**186** and **187**)^{296–298} Loh and Koh selected 5-HMF (**119**) and levulinic acid (**122**) as biomass-derived starting materials (Scheme 29).²⁹⁹ The tetrahydropyran moiety was synthesized from **119** which was benzyl protected and subjected to an aldol reaction. Oxidation of the racemic product and asymmetric transfer hydrogenation furnished β -hydroxyester **180**. Although the non-stereoselective aldol reaction/oxidation/asymmetric reduction sequence does not look very eco-friendly at first glance, it turned out to be the only suitable way to access enantiopure **180**. Asymmetric Mukaiyama aldol reactions as well as dynamic enzymatic kinetic resolutions of racemic **180** were attempted but neither of them provided the desired outcome in terms of yield and enantiomeric excess.

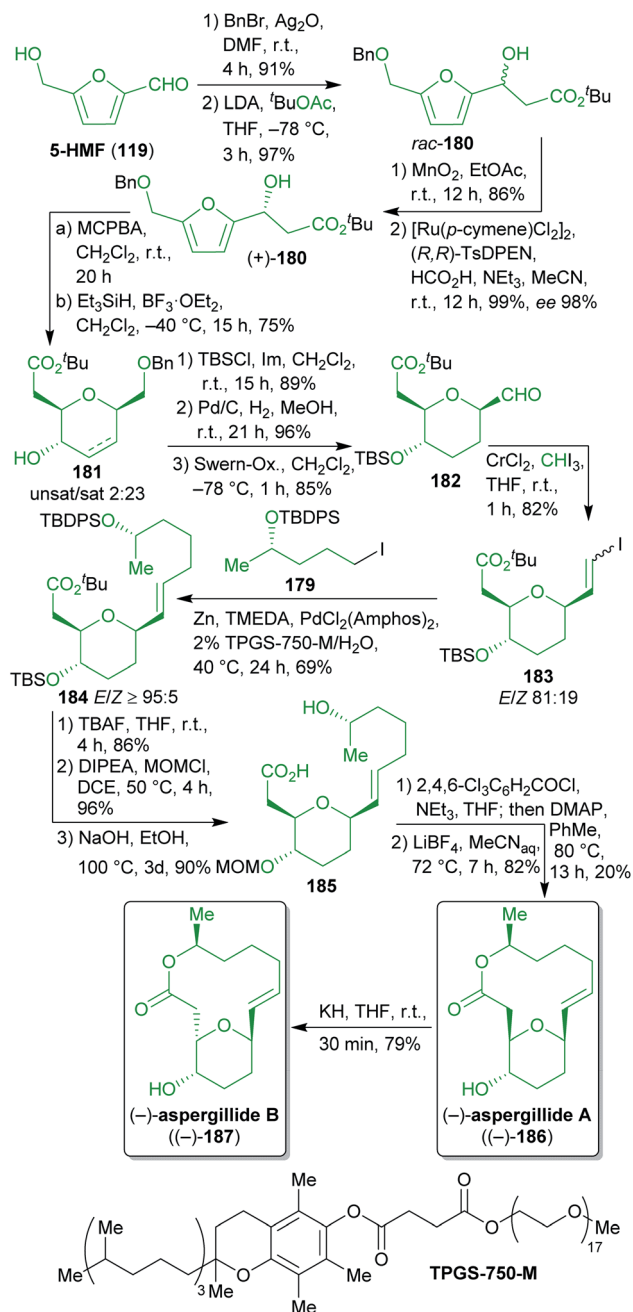


Scheme 27 Synthesis of (+)-chloriolide ((+)-**177**) from levoglucosenone (**115**).



Scheme 28 Synthesis of levulinic acid (**122**) derived intermediate **179** for the synthesis of aspergillides A (**187**) and B (**186**).





Scheme 29 Synthesis of aspergillides A ((-)-187) and B ((-)-186) from 5-HMF (119) and LA (122).

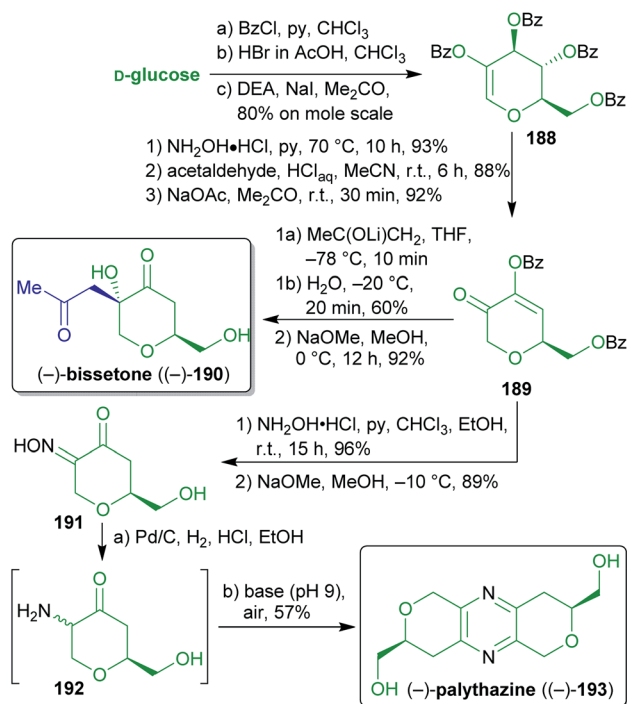
Achmatowicz rearrangement and reductive deoxygenation gave a mixture of dihydro- and tetrahydropyran **181**. After O-protection, hydrogenation removed the double bond and the benzyl group. The resulting primary alcohol was subjected to Swern oxidation and the following Takai iodoolefination (iodoform is e.g. available from the reaction of ethanol with I_2 in alkaline medium)³⁰⁰ furnished the first 5-HMF-derived building block **183**.

On the other hand, levulinic acid (**122**) was reduced to the respective racemic diol, which was subjected to dynamic enzymatic kinetic resolution and the desired enantioenriched alcohol was TBDPS protected to obtain **184**. Ester hydrolysis and

iodination furnished the second building block **179** in excellent yield and ee (Scheme 28). Both building blocks were coupled by means of a Negishi reaction with high selectivity in favor of the desired *E*-isomer. An eco-friendly micelle-based variant using the commercially available amphiphile TPGS-750 M³⁰¹ in water and *in situ*-generation of the organozinc reagent was employed.^{302–304} After cleavage of the silyl protecting groups, a MOM group was installed and the ester was saponified to yield seco-acid **185** which was already used by Fuwa *et al.* as an intermediate and was converted to (-)-**186** by Yamaguchi esterification.³⁰⁵ Epimerization with potassium hydride gave (-)-**187**.³⁰⁶

Throughout this remarkable sequence, a number of steps were intentionally conducted in accordance with the principles of “green” chemistry. As already pointed out, the Negishi coupling of **183** and **179** is an example of “greener” chemistry and the dynamic enzymatic kinetic resolution also ensures a high overall yield.

2.2.2.7. (-)-Bisetone and (-)-palythazine. For the first total syntheses of the marine natural products bisetone (**190**)³⁰⁷ and palythazine (**193**)³⁰⁸ Lichtenthaler and coworkers^{309–311} used glucose as a biomass-derivable starting material in a class-transcendent fashion (Scheme 30). Both sequences proceed *via* the dihydropyranone **189**, which can be prepared from *D*-glucose on a molar scale in six steps *via* the hydroxyglucal ester **188**.^{312–314} Addition of the lithium enolate of (potentially xylochemical) acetone and subsequent protecting group cleavage furnished enantiopure (-)-bisetone ((-)-**190**). The nucleophilic attack is favored from the axial side and therefore leads to the product with the desired relative configuration.

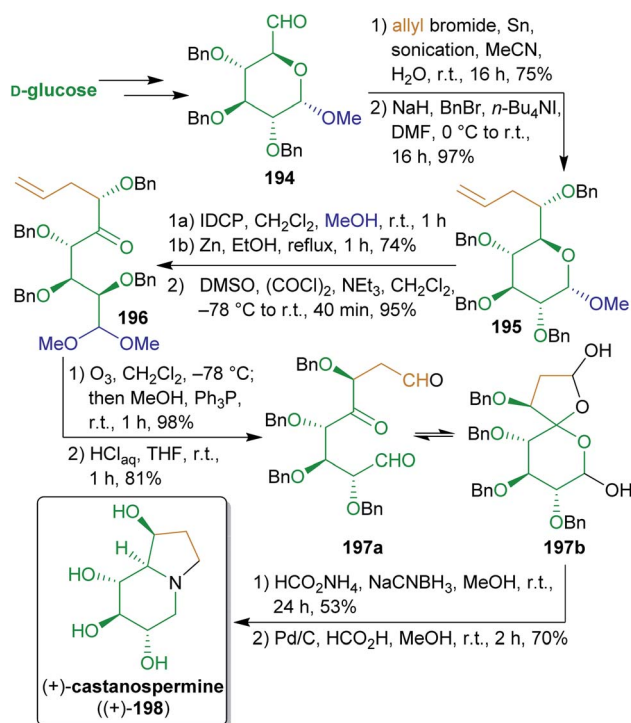


Scheme 30 First total syntheses of (-)-bisetone ((-)-190) and (-)-palythazine ((-)-193) from glucose.

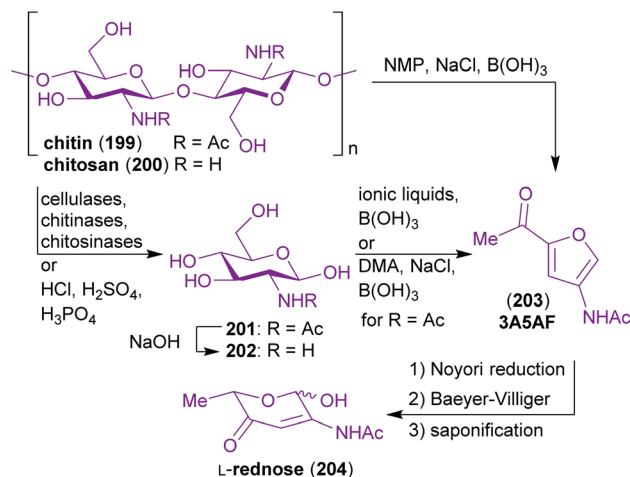


For the synthesis of (–)-**193**, the carbonyl group of **189** was converted into the oxime **191** which spontaneously underwent oxidative dimerization into enantiopure (–)-palythazine ((–)-**193**) upon exposure to air after global deprotection and oxime reduction. The absolute configuration of (–)-palythazine ((–)-**193**) was proven through this stereospecific synthesis. These concise and straightforward syntheses make excellent use of biomass-based D-glucose as an enantiopure starting material (ex-chiral pool strategy) to prepare non-carbohydrate natural products. Acetone^{290,291} was used as a potentially renewable C₃-synthon. Additionally, in contrast to classic carbohydrate chemistry, only a single protecting group transformation was performed throughout the entire sequence.

2.2.2.8. (+)-Castanospermine. Mootoo and coworkers^{315,316} utilized the hydroxyl substitution pattern of D-glucose for the synthesis of polyhydroxyindolizidine alkaloid (+)-castanospermine ((+)-**198**).³¹⁷ The synthesis of this plant-derived natural product commenced with the allylation of aldehyde **194** which is readily available from glucose (Scheme 31).^{318–320} The desired *threo*-epimer was the major product (9 : 1 selectivity) and could be separated by chromatography. After benzylation, treatment with iodonium dicollidine perchlorate (IDCP), reductive elimination and Swern-oxidation furnished ketone **196**. Ozonolysis and acetal hydrolysis gave key tricarbonyl intermediate **197a** in the lactol form **197b**, which was subjected to triple reductive amination. During this reaction only 5% of the undesired C8-epimer was formed. Global deprotection furnished enantiopure (+)-castanospermine ((+)-**198**) with a high yield of 22% over nine steps starting from **194**.



Scheme 31 Synthesis of polyhydroxyindolizidine alkaloid castanospermine (**198**).



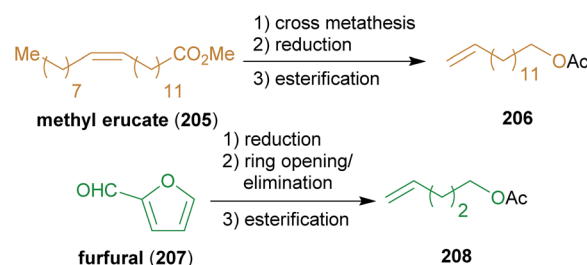
Scheme 32 The chemical structure of chitin/chitosan and examples of starting materials derived thereof.

This remarkable work makes formidable use of the innate stereoinformation of bio-based glucose to synthesize this stereochemically demanding natural product.

2.3. Chitin and chitosan

Chitin **199** and chitosan **200** are the chemical constituents of the exoskeleton of crustaceans and insects as well as of cell walls of molluscan organs and fungi. This makes it the second most abundant biopolymer (after cellulose)³²¹ and the most abundant nitrogen containing biopolymer on earth.³²² Similar to the structure of cellulose, chitin is a linear polysaccharide, but unlike cellulose it is composed of $\beta(1 \rightarrow 4)$ -linked 2-acetamido-2-deoxy-D-glucopyranose (N-acetylglucosamine, GlcNHAc **201**) monomers (Scheme 32). As depicted in Scheme 32, the C-2-substituent of the sugar-derived monomer is either an acetamido- or a free amino group. The term chitin refers to the material with >50% of acetylated amino groups while the material with a lower degree of N-acetylation is called chitosan.³²³

2.3.1. Valorization of chitin and chitosan. The utilization of chitin and chitosan for the production of biofuel, chemical raw materials or functional materials with applications in chemistry and pharmaceuticals has been called the “shell biorefinery”^{322,324} or – hence its predominantly marine origin – the “ocean-based biorefinery”.³²⁵ Although this is a very promising feedstock due to its abundance, its availability as a waste



Scheme 33 Schematic synthesis of terminal olefins **206** and **208** for the synthesis of rhizochanilin C (**217**).



product from food production and its unique potential as a source for nitrogen containing raw materials, the field of chitin valorization is just emerging. Extensive reviews and summaries about its structure and biosynthesis can be found elsewhere.^{326–328} For detailed information about the valorization of this promising feedstock we refer to existing literature.^{322–325,329–332} Therefore, we will focus on a small number of low molecular weight organic compounds obtainable from chitin or chitosan that are relevant for the synthesis of natural products within the scope of this review. As for other biopolymers, the compounds accessible from chitin and chitosan vary with the conditions used for depolymerization.

The natural material in the form of shrimp, crab or lobster shells has to be digested by grinding, deproteinization, demineralization, discoloration and drying prior to depolymerization.³³³ The prepared chitin and chitosan can be cleaved directly into the corresponding amino sugars N-Ac-glucosamine (GlcNHAc, **201**) or 2-amino-2-deoxy-glucose (GlcNH₂, **202**) either enzymatic or with inorganic acids (Scheme 32).^{324,334–337} GlcNHAc can be deacetylated to yield GlcNH₂ or be converted to two highly promising N-containing starting materials that are challenging to make from other resources.

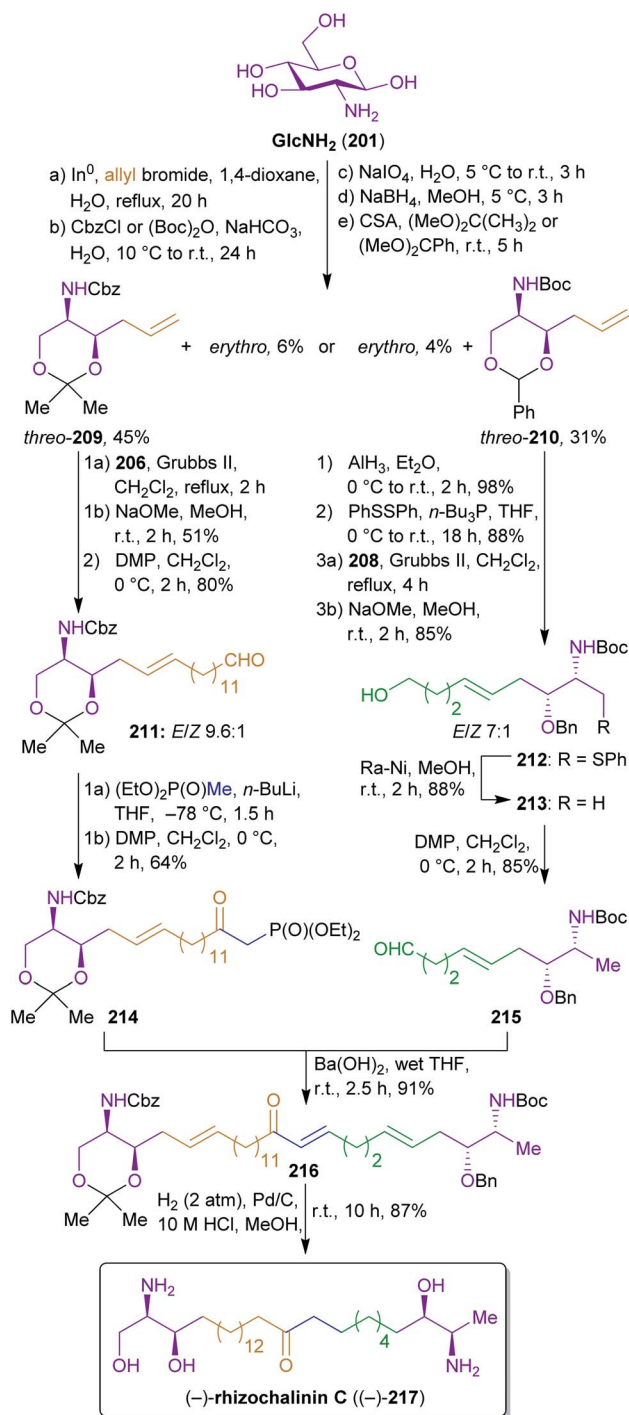
The furan derivative 3-acetamido-5-acetylfuran (3A5AF, **203**) can easily be prepared from **201** in a single step^{338–340} or directly from **199**.^{338,341} 3A5AF (**203**) can in turn be converted to L-red-nose (**204**), which contains a β-aminoenone moiety rarely seen in carbohydrates, in a three step sequence.³⁴²

2.3.2. Natural product syntheses using chitin/chitosan derived starting materials

2.3.2.1. (–)-Rhizochalinin C. Molinski's and Ko's synthesis of rhizochalinin C (**217**)^{343,344} is a good example for the potential of the combinatorial use of biomass derived starting materials.³⁴⁵ Their approach to construct this L-threo, α,ω-bifunctionalized sphingoid base combines the use of D-glucosamine from chitin/chitosan as an element of the chiral pool for extracting the stereocenters and fats/oils as well as hemicellulose derived starting materials to build the largest part of the carbon backbone. The key achievement of this work is the conversion of **202** into the useful synthons for L-threo sphingoid bases **209** and **210** by a sequence starting with a Barbier reaction with allyl bromide, followed by N-protection, glycol cleavage, reduction and diol protection (Scheme 34). The allyl bromide used for the Barbier reaction is derivable from glycerol which is produced on a megaton scale by hydrolysis of fats and oils³⁴⁶ through allyl alcohol as an intermediate.^{217,347}

The respective threo-diastereomers were subjected to olefin metathesis and further functionalized to furnish the respective Western **214** and Eastern halves **215**, which were coupled by a Horner reaction. Prior to the olefin metathesis, a switch of the protecting groups was conducted to prepare the required deoxygenation.

The reactant for cross-metathesis with threo-**209**, tetradec-13-enyl acetate (**206**), can be easily obtained by cross metathesis of methyl erucate (**205**) with ethylene,^{348,349} followed by reduction and esterification (Scheme 33). Likewise, the olefin **208** could be prepared from hemicellulose via furfural **207** which is hydrogenated to tetrahydrofurfuryl alcohol.³⁵⁰ A ring opening/



Scheme 34 Synthesis of sphingoid base synthons and (–)-rhizochalinin C ((–)-217) from **202**.

elimination sequence gave pent-4-ene-1-ol³⁵¹ which was esterified to **208**. The synthesis of the phosphonate **214** is conducted with diethyl methylphosphonate which in turn can be synthesized from methanol and triethyl phosphite.³⁵² Hydrogenation under strongly acidic conditions ensured global deprotection and saturation of the Horner product **216** in a single step to furnish stereopure (–)-rhizochalinin C ((–)-217). This synthesis



makes excellent use of a variety of sustainable building blocks to construct a rather demanding natural product.

Unfortunately, frequently used methods such as glycol cleavage, cross metathesis or Horner reactions are not very atom economic.

2.3.2.2. (-)-Pochonicine. The total synthesis of fungal polyhydroxylated pyrrolizidine (-)-pochonicine hydrochloride ((-)-226·HCl)³⁵³ from GlcNHAc (**201**) by Takahashi *et al.*³⁵⁴ is one of the numerous examples where the originally proposed absolute configuration of the natural product had to be revised based on synthetic work.

Starting from monothiolacetal **218**, which was prepared from **201**,³⁵⁵ the configuration of the hydroxyl group at C-3 and the N-protecting group were switched (Scheme 35). Reductive acetal opening and nucleophilic attack of the nitrogen at C-5 led to pyrrolidine **221**. After debenzoylation and oxidation, a nucleophilic allylation was performed through attack of a Grignard reagent. Both diastereomers (*threo*- and *erythro*-**222**) were formed in this step. The synthesis of (-)-pochonicine ((-)-226) was conducted with the *erythro*-isomer but the *threo*-isomer was also advanced to obtain the respective C-1 and C-3 epimers of **226**. The structure shown in Scheme 35 corresponds to the originally proposed configuration³⁵³ but comparison of the analytical data proved to be inconsistent with that of the natural product. Dihydroxylation of the terminal olefin again led to a mixture of diastereomers **224**, whereas the 7-*S*-epimer led to (-)-**226** and the 7-*R*-epimer to the respective C-3-epimer (not shown). After conversion to the hydrochloride, the observed optical rotation of the synthetic product proved to be opposite to the one of the isolated compound.

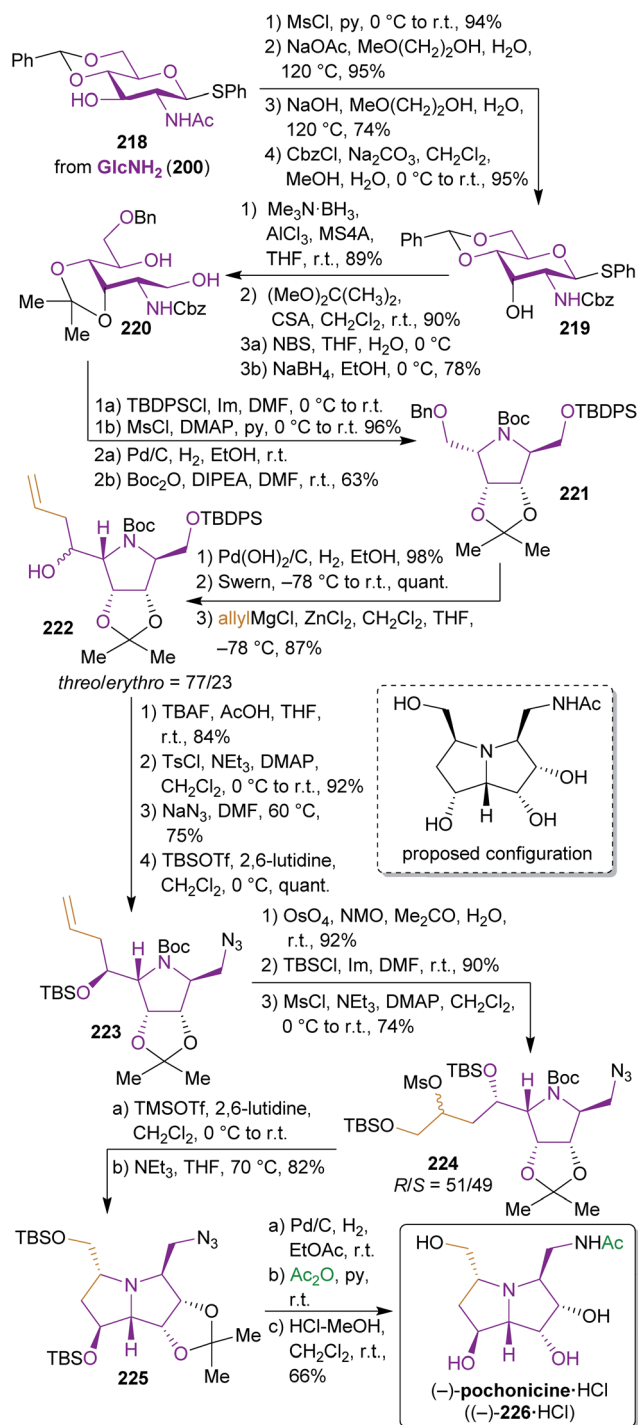
In this noteworthy work, four different diastereomers were synthesized from two common precursors to clarify the absolute configuration of this stereochemically demanding natural product. Unfortunately, the use of protecting group chemistry was inevitable due to the high degree of functionalization of the intermediates and final product.

2.3.2.3. (-)-Allosamizoline. As mentioned earlier, a major advantage of bio-based starting materials is the often high degree of functionalization, in particular with respect to stereogenic centers. Therefore, GlcNHAc and GlcNH₂ are ideal templates for the synthesis of stereochemically demanding natural products. Several groups have utilized GlcNH₂ (**201**) in this respect for the synthesis of (-)-allosamizoline ((-)-231),^{356–361} a bacterial pseudo-aminosugar with chitinase inhibitory activity.^{362–365} For this potentially biomimetic approach,³⁶⁶ two main routes emerged for the crucial intramolecular ring closure to form the cyclopentane ring (Scheme 36). While Simpkins and Whittle used a radical ring closure of thiocarbamate **228** and an oxime ether **229**,^{358,359} the Tatsuta and Kitahara groups opted for an oxidative cycloaddition to generate isoxazoline intermediate **235**.^{356,360}

All three ways converge into the same carbamate intermediate **230** and they rely on the same carbon sources to construct **231**. This work highlights how simple biomass-based building blocks, namely GlcNH₂ and dimethylamine (available from

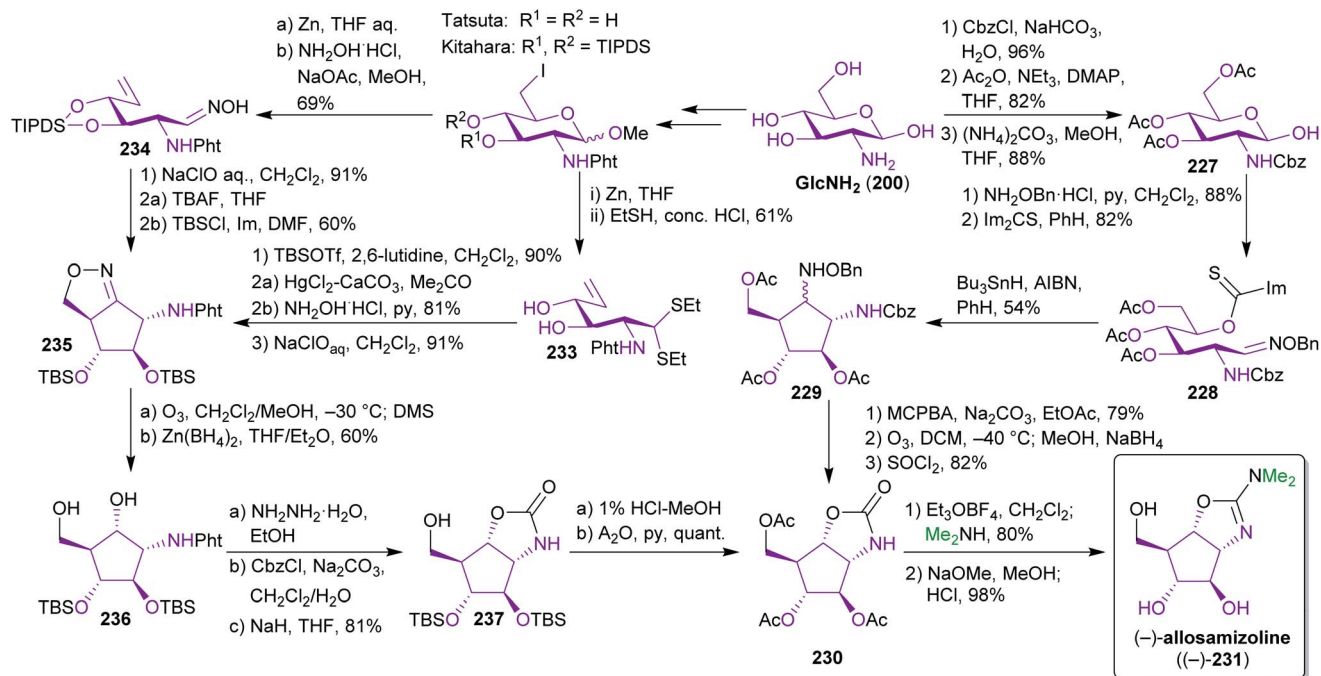
methanol and ammonia)³⁶⁷ can be transformed into valuable natural products without the use of fossil carbon sources.

2.3.2.4. Proximicin A. The nitrogen-containing furan derivative 3A5AF (**203**) was utilized by Sperry and coworkers for a proof-of-concept synthesis of proximicin A (**241**),³⁶⁸ a potential chemotherapeutic compound.^{369,370} It is the first natural product synthesis that uses this unique bio-based starting material, which appears to be perfectly suited for the synthesis



Scheme 35 Synthesis of (-)-pochonicine hydrochloride ((-)-226·HCl) from GlcNHAc.



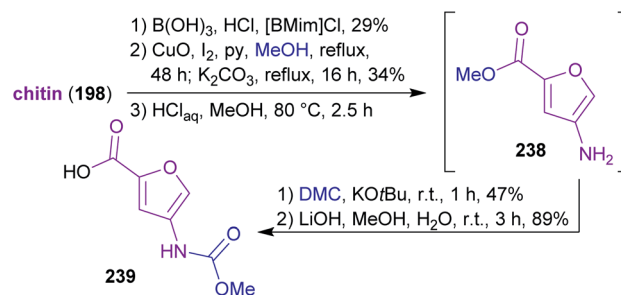
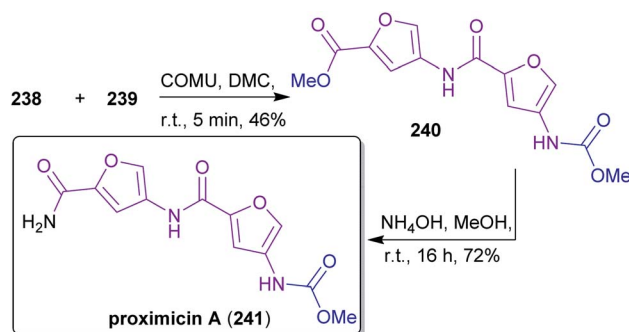
Scheme 36 Synthesis of (-)-allosamizoline ((-)-231) from GlcNH₂.

of 241. Proximicin A was produced in a seven-step sequence from chitin *via* the key intermediates 238 and 239 (Scheme 37) simultaneously obeying the fundamentals of green chemistry (Scheme 38). In this remarkable work, only “green” solvents ([BMim]Cl – 1-butyl-3-methylimidazolium chloride, MeOH, H₂O, DMC) and procedures were used while it still compared well with former “non-green” syntheses of 241 in terms of step count and yields.^{369,370} The non-toxic dimethyl carbonate (DMC), which can be made directly from methanol and carbon monoxide in the presence of CuCl and oxygen,^{371–373} was used for the introduction of the carbamate moiety³⁷⁴ instead of the conventional methyl chloroformate. Furthermore, the amide coupling of the intermediates 238 and 239 was conducted with the uronium-based coupling reagent COMU³⁷⁵ ((1-cyano-2-ethoxy-2-oxoethylideneaminoxy)dimethylamino-morpholinocarbenium hexafluorophosphate) instead of the conventional, potentially explosive 1-hydroxybenzotriazole derivatives (*e.g.* TBTU, HATU, HBTU).

2.4. Fats and oils

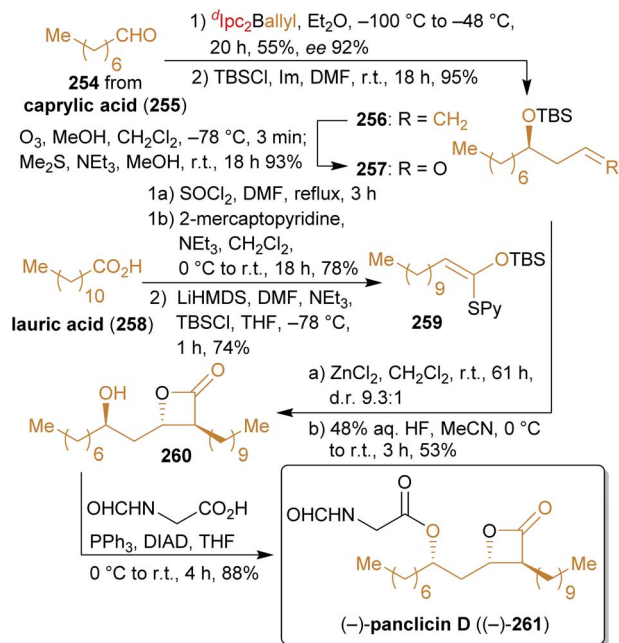
Fats and oils, either of plant or animal origin, occur in the form of tri-, di- and monoglycerides with varying compositions of fatty acids depending on their origin. The annual production reaches almost 200 Mt and has been increasing over the last decades.^{376,377} Although this figure indicates a very large industrial product class, one has to keep in mind that the largest fraction of this amount is used for food and feed. Furthermore, with the advent of biodiesel, the ratio of utilization of fats and oils for food/feed *versus* industry was slowly shifting from 86 : 14 to 80 : 20 over the past few decades.³⁷⁸ If this ethical dilemma could be solved, fats and oils would represent

a structurally ideal renewable feedstock not only for the production of chemical raw materials and synthetic chemistry but also for fuel and polymer production.

Scheme 37 Synthesis of key intermediates 238 and 239 for proximicin A (241) from chitin *via* 3A5AF (203).

Scheme 38 Closing amide coupling and amide synthesis for proximicin A (241).



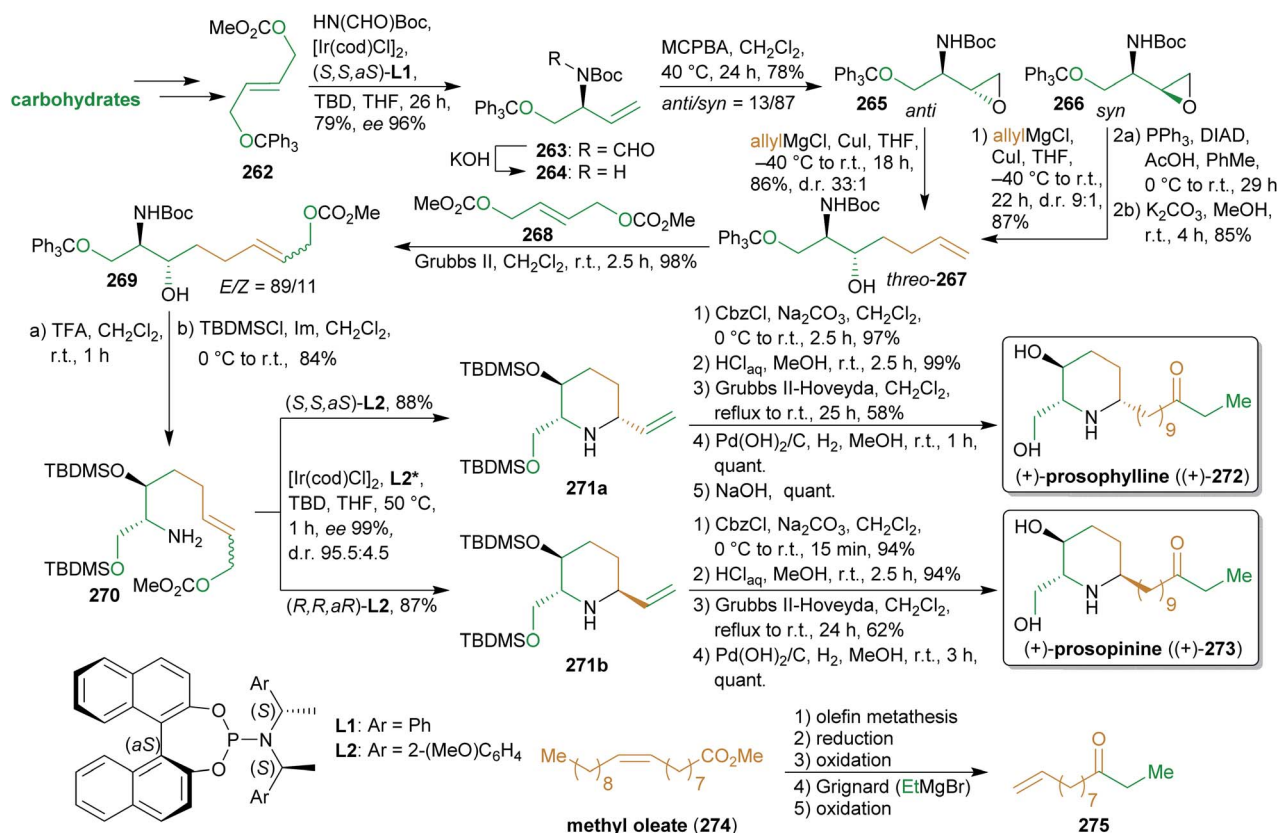
Scheme 41 Synthesis of (-)-panclicin D ((-)-261) by Romo *et al.*

materials in the form of lauric acid (**258**) and caprylic acid (**255**) as the main carbon sources as well as allyl diisopinocampheylborane as a terpene/glycerol-derivable chiral allylating

agent (Scheme 41). While lauric acid is very abundant in laurel oil (hence the name), in coconut milk and oil as well as in palm kernel oil, caprylic acid can also be found in coconut oil, albeit in much lower concentration.^{406,407} Caprylic acid can be produced by *de novo* synthesis from bio-engineered yeast or *E. coli* strains^{408–410} or by anaerobic microbial fermentation from ethanol and acetate *via* chain elongation.^{411,412}

Lauric acid is converted to the ketene thioacetal **259** which is subjected to a tandem Mukaiyama aldol-lactonization with aldehyde **257** to form the β -lactone ring. For the synthesis of **257**, methyl caprylate is converted to octanal (**254**)⁴¹³ followed by enantioselective addition of an allyl group, protection and ozonolysis. After desilylation, *N*-formyl glycine was attached by a Mitsunobu reaction to furnish (-)-panclicin D ((-)-**261**). The use of little functionalized starting materials for the formation of this interesting natural product makes this synthesis remarkable.

2.4.2.3. (+)-Prosophylline and (+)-prospinine. The antibiotic piperidine alkaloids (+)-prosophylline ((+)-**272**)⁴¹⁴ and (+)-prospinine ((+)-**273**)^{415,416} were synthesized by Helmchen *et al.* *via* an iridium-catalyzed allylic substitution (Scheme 42).^{417,418} This key reaction was used twice during the synthesis to introduce and modify the required stereochemistry. The first application of this methodology was the conversion of the trityl-protected carbonate **262** available from dimethyl fumarate⁴¹⁹ to allylic amine **264**. Dimethyl fumarate can be obtained from malic acid or furfural (**207**),^{420–422} both available from cellulose. After epoxidation,



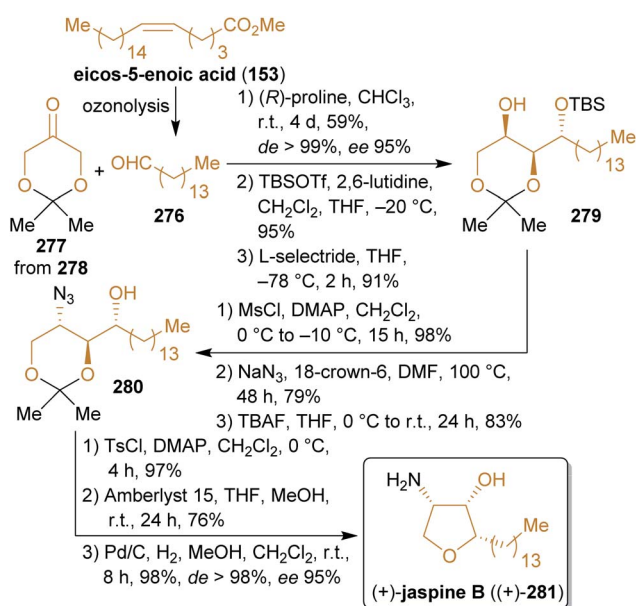
Scheme 42 Synthesis of (+)-prosophylline ((+)-272) and (+)-prospinine ((+)-273). TBD = 1,5,7-triazabicyclo[4.4.0]dec-5-ene.



Grignard reaction and cross metathesis with a biscarbonate likewise accessible from dimethyl fumarate, the nitrogen was deprotected to enable the ring closure, while the free hydroxy group was protected. Both diastereomers from the epoxidation reaction were convergently converted to the same *threo*-amino alcohol **267** with the desired configuration. Again, allylic substitution with both enantiomers of the chiral ligand (**L2**) led to the respective piperidine diastereomers **271a, b** with excellent ee and high dr which is the result of extensive optimization studies. N-protection, olefin metathesis with dodec-1-en-10-one (**275**), hydrogenation and Cbz-removal led to the desired natural products **272** and **273**. Ketone **275**⁴²³ is produced from the cross metathesis product of methyl oleate (**274**) with ethylene.²⁷⁵

This synthesis is characterized by the use of powerful methodology for the catalytic introduction of chiral information in combination with the utilization of various sustainable carbon sources to produce two alkaloids through a common precursor.

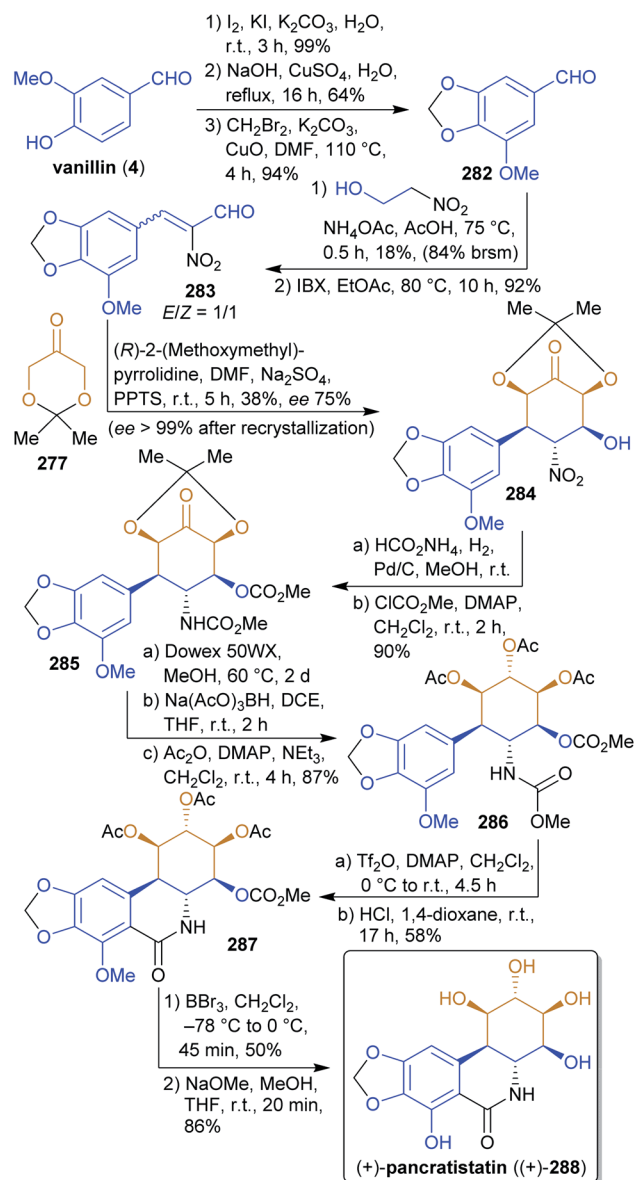
2.4.2.4. (+)-Jaspine B. The cytotoxic marine natural product jaspine B (**281**) received great attention since its isolation and elucidation in 2002^{424,425} and numerous synthetic approaches have been published in the past decade^{426–436} due to its remarkably low IC₅₀-values against a variety of tumor cell lines.⁴²⁴ Among these syntheses, the concise procedure of Enders and coworkers stands out, which starts from protected dihydroxyacetone **277** and 1-pentanal (**276**). Dihydroxyacetone (**278**) is produced on a large scale from glycerol by fermentation.⁴³⁷ The acetonide **277** is subjected to an organocatalyzed aldol reaction with **276** (Scheme 43). After stereoselective reduction of the keto group, the generated hydroxy group was converted to an azide moiety under inversion of the configuration. The same sequence was used for the ring closure to furnish the tetrahydrofuran ring with the required configuration. After hydrogenation of the azide group, (+)-jaspine B (**281**) was obtained in high stereoselectivity.



Scheme 43 (+)-Jaspine B ((+)-**281**) synthesis.

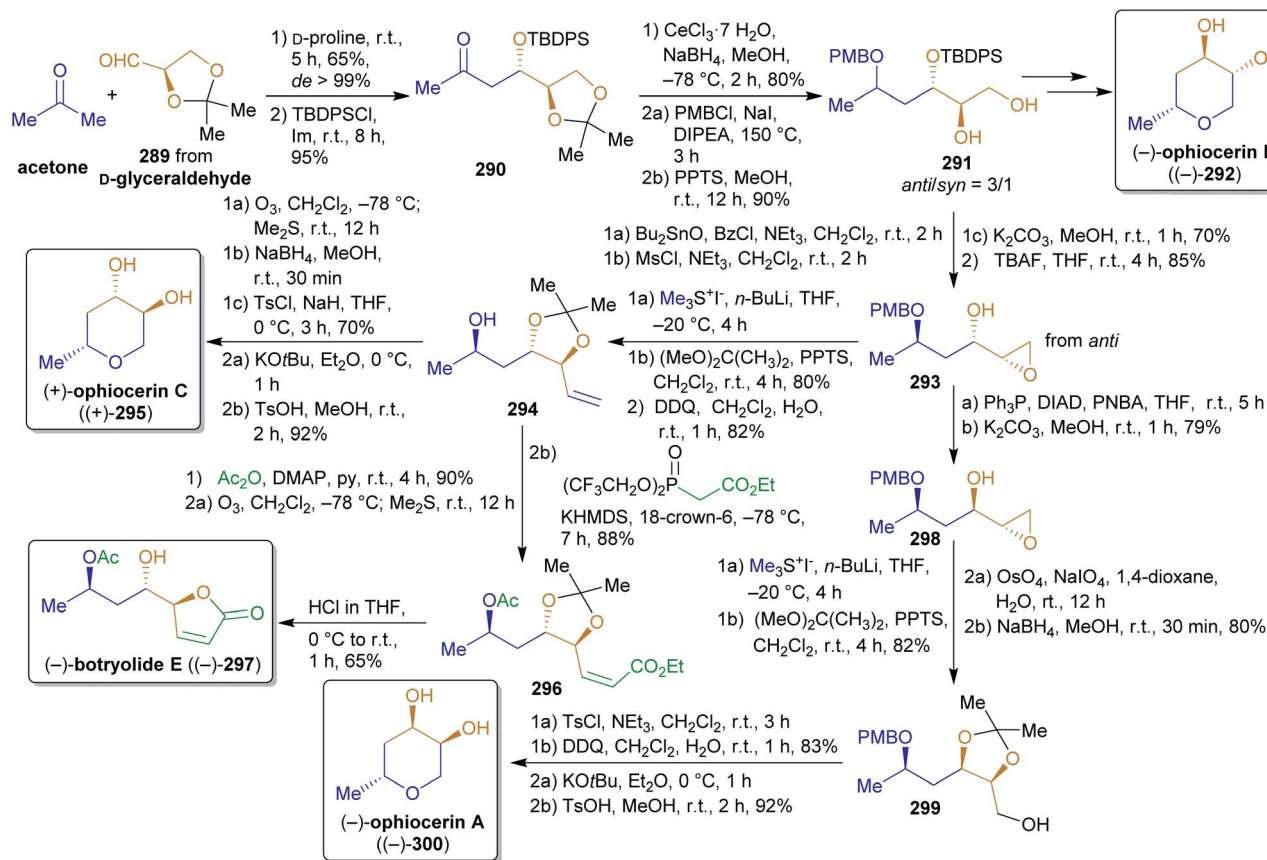
2.4.2.5. (+)-Pancratistatin. The antiproliferative isocarboxtyril alkaloid pancratistatin (**288**)^{438,439} was synthesized by Alonso *et al.*⁴⁴⁰ from **277** and the xylochemical vanillin (**4**). The correct stereochemistry is established by the organocatalyzed reaction of **277** with nitroenal **283**⁴⁴¹ during which five stereocenters are formed (Scheme 44). Nitro group reduction, carbamate formation and reduction of the keto group gave the precursor **286** for the Bischler–Napieralski reaction, after which global deprotection led to (+)-pancratistatin ((+)-**288**). 2-Nitroethanol can be considered a xylochemical since it is produced from nitromethane (itself available in a single operation from methanol)⁴⁴² and formaldehyde.⁴⁴³ The presented approach is very straightforward and uses renewable inexpensive starting materials as well as simple synthetic methods.

2.4.2.6. Ophiocerin and (-)-botryolide E. The following synthesis of the ophiocerin A–C (**300**, **292** and **295**) and

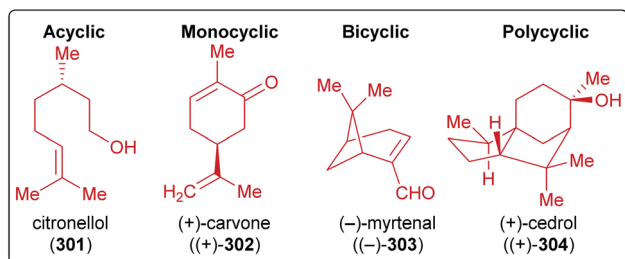


Scheme 44 Total synthesis of (+)-pancratistatin ((+)-**288**) by Alonso *et al.*



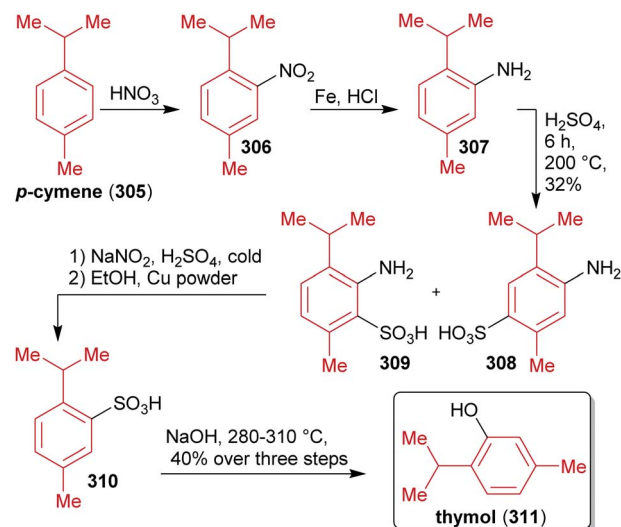


Scheme 45 Synthesis of ophiocerin A–C (300, 292 and 295) and botryolide E (297).



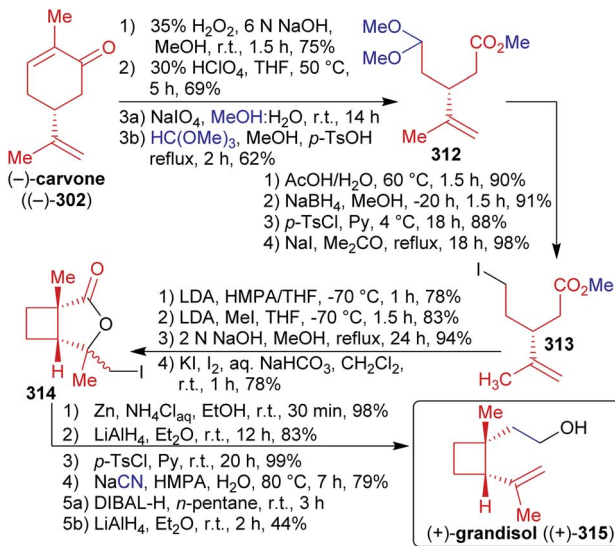
Scheme 46 Different classes of terpenes.

botryolide E (297)⁴⁴⁴ is an excellent example of the combination of a biomass-derived chiral precursor (isopropylidenglyceraldehyde (289)), other renewables-derived simple building blocks and organocatalysis for the formation of a variety of natural products (Scheme 45). Like dihydroxyacetone, glyceraldehyde can be generated from glycerol, e.g. by aerial oxidation over platinum catalysts,³⁸⁶ or directly by fermentation of carbohydrate biomass.⁴⁴⁵ Proline-catalyzed aldol reaction of acetonide-protected aldehyde 289 and acetone led to the respective β -hydroxy ketone 290 in excellent *de* which was protected with a TBDPS group. Before the cumene process was introduced, acetone was produced by Weizmann's acetone–butanol–ethanol (ABE) fermentation of carbohydrates through *Clostridium acetobutylicum*.⁴⁴⁶ Another source of

Scheme 47 Synthesis of thymol (311) from *p*-cymene (305).

acetone is the pyrolysis and dry distillation of wood and therefore it is considered a xylochemical.^{290,291} Reduction, PMB-protection and acetonide cleavage led to the pivotal intermediate 291 and all four natural products that were mentioned earlier were synthesized from this *anti*-diastereomer. For the synthesis of ophiocerin A and C (300 and 295), the secondary





Scheme 48 Synthesis of (+)-grandisol ((+)-315) from (-)-carvone ((-)-302).

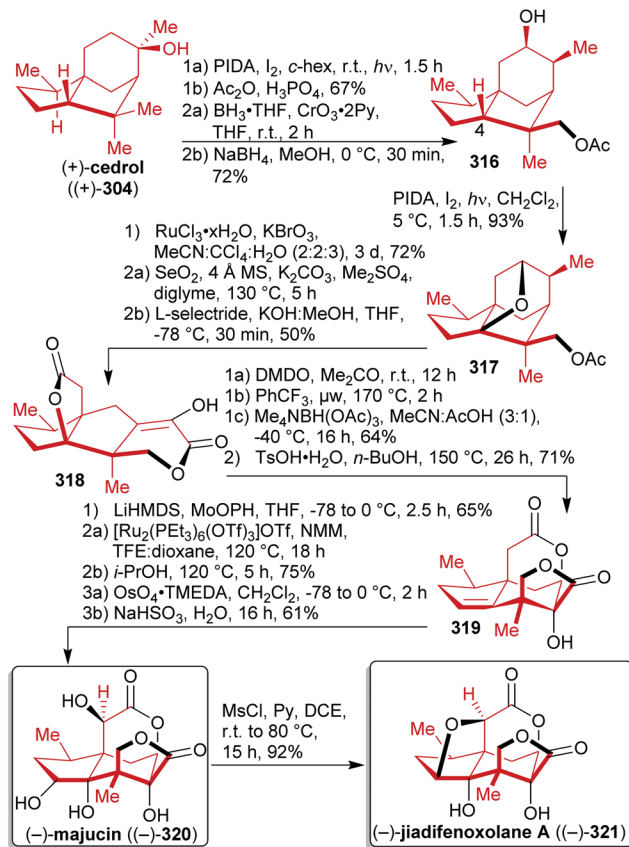
hydroxy group was converted into a leaving group and the *syn*-epoxy alcohol 293 was formed by nucleophilic substitution. For 300, the inversion of alcohol, epoxide opening, acetonide protection, Lemieux–Johnson oxidation and reduction were performed. Trimethylsulfonium iodide was used for the olefin synthesis from epoxide 293 (available from dimethylsulfide and iodomethane,⁴⁴⁷ both methanol-derived). After PMB cleavage, the primary alcohol was converted into a leaving group and the tetrahydropyran ring was closed by nucleophilic substitution. Final acetonide cleavage furnished (-)-ophiocerin A ((-)-300). Ophiocerin C (295) was synthesized by essentially the same sequence except that no inversion was conducted and that PMB deprotection was performed prior to olefin cleavage by ozonolysis to obtain a suitable intermediate for the synthesis of botryolide E (297). Likewise, ophiocerin B (292) was prepared *via* the respective *anti*-epoxy alcohol (sequence not shown).

Starting from the olefin 294, botryolide E was synthesized by ester synthesis, ozonolysis and the Still–Gennari modification of the Horner reaction to obtain *E*-olefin 296. The required phosphonate can be produced from an α -haloacetic acid derivative and is therefore accessible by fermentation of carbohydrates through acetic acid.^{347,448,449} Acid catalyzed acetonide cleavage and lactone formation produced (-)-297.

The use of simple bio-based starting materials and pivotal intermediates for the stereochemically flexible synthesis of natural products are notable key features of this work.

2.5. Terpenes

Terpenes represent abundant and renewable, inexpensive and versatile chiral starting materials and were employed in natural product synthesis ever since.^{80,450} Furthermore, terpenes are one of the largest and most diverse classes of plant produced organic compounds and do not directly compete with food production.^{451–454}

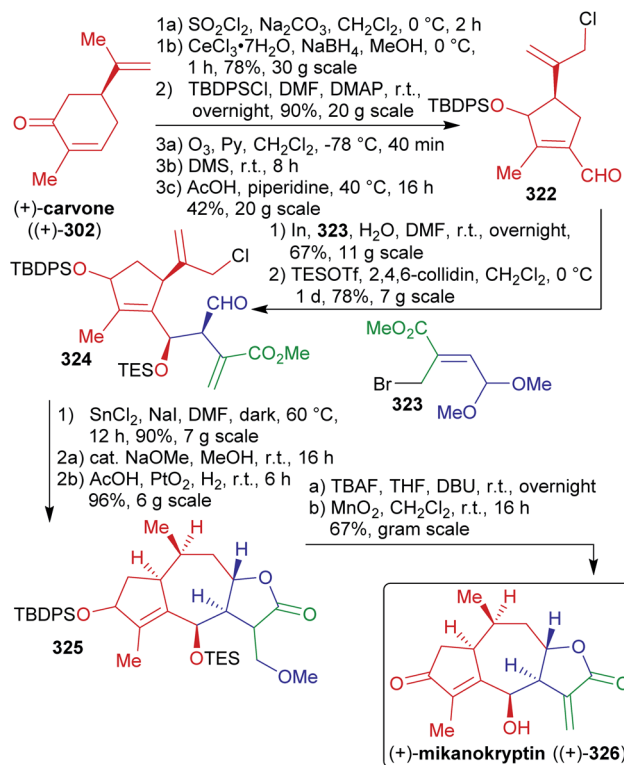


Scheme 49 Synthesis of (-)-majucin ((-)-320) and (-)-jiadifenoxolane A ((-)-321) from (+)-cedrol ((+)-304).

2.5.1. Valorization of terpene feedstock. Together with the amino acids and the carbohydrates, terpenes form the “chiral pool” (see the Introduction).^{455–457} Terpenes are hydrocarbon compounds usually containing one or more C=C-double bonds and having a limited degree of oxygenation. They can be divided into subgroups named after their carbon count, since isoprene units containing five C-atoms are the biosynthetic precursors of all terpenes:⁴⁵² the monoterpenes (C₁₀), the sesquiterpenes (C₁₅), the diterpenes (C₂₀), *etc.* They also differ in the arrangement of the isoprenoid units (acyclic, mono- or polycyclic) and in their oxidation state (Scheme 46). Despite the enormous advances in asymmetric synthesis in the 20th century, terpenes are still widely used as chiral starting materials.⁴⁵⁸ Furthermore, they can be useful as potential fuels,⁴⁵⁹ agents for the chemical communication of plants, flavor enhancement and pesticides,^{460,461} or as a source of chirality in catalysts.⁸¹

The major sources of monoterpenes are turpentine oil (a waste product of paper pulp industry, contains mainly α - and β -pinene),⁴⁶² and citrus oil (contains mainly (+)-limonene),⁴⁶³ a co-product of citrus juice production.⁴⁵² Terpenes can also be transformed and functionalized by biotechnological methods or biotransformations.^{452,464–466} For further information about sources of terpenes, their use in total synthesis and utilization as chiral building blocks, the reader may be referred to the literature.^{80,450,452}





Scheme 50 Synthesis of (+)-mikanokryptin ((+)-326) using terpene- and wood-derived building blocks.

2.5.2. Natural product syntheses using terpene feedstock starting materials

2.5.2.1. Thymol. Phillips *et al.* published a five-step synthesis of natural thymol (**311**) in 1920.⁴⁶⁷ The synthesis commenced with nitration of natural *p*-cymene (**305**)⁴⁶⁸ followed by Béchamp reduction. Sulfonation gave two isomeric products

309 and **308**. Subsequent diazotation/reduction led to sulfonic acid **310**. Fusion with NaOH finally produced thymol (**311**)⁴⁶⁹ (Scheme 47).⁴⁶⁷

2.5.2.2. (+)-Grandisol. In 1992, Mori *et al.* reported a synthesis of the natural product (+)-grandisol ((+)-**315**) in eighteen steps and ≥98% ee (analyzed by GC).⁴⁷⁰

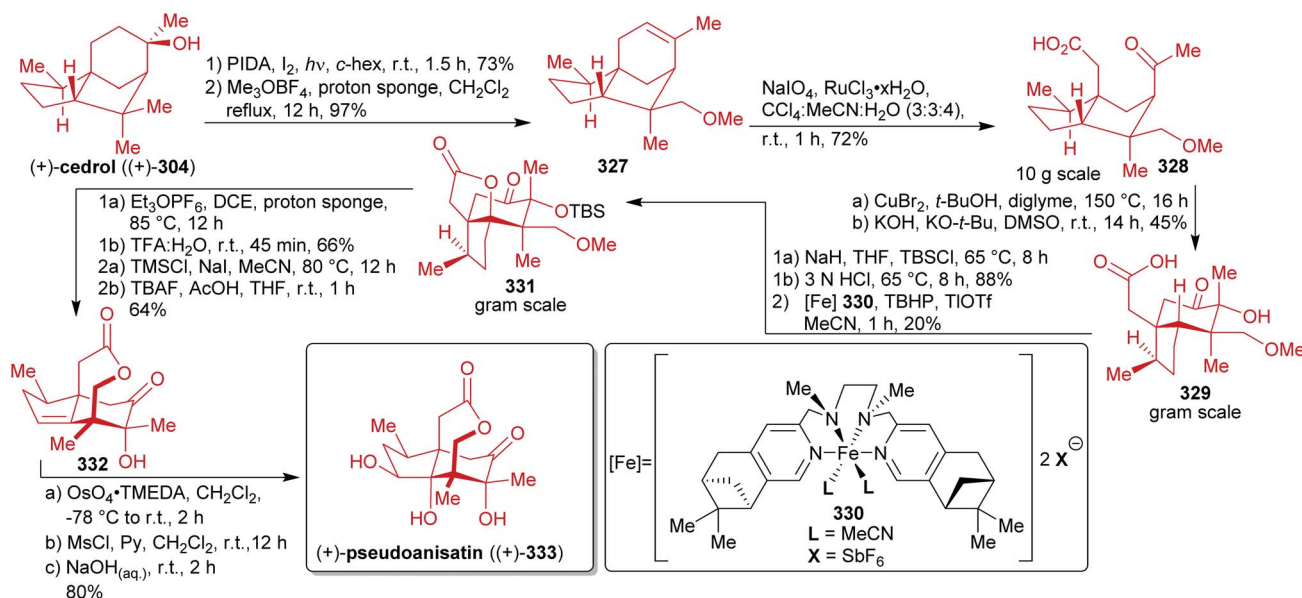
The synthesis commenced with epoxidation of (–)-carvone ((–)-**302**), accessible from biomass,^{471,472} which is ring-opened oxidatively in a four-step sequence to yield acetal ester **312**. The latter was reduced, tosylated, and subjected to a nucleophilic substitution by iodide furnishing iodoester **313**. Subsequent cyclization, methylation and iodolactonization led to **314** (Scheme 48). The enantioselective synthesis was concluded by multiple reduction reactions, followed by tosylation, cyanation and further reductions affording the natural product (+)-grandisol ((+)-**315**).^{470,473}

Sodium cyanide is currently produced by the Andrussow process from methane and ammonia^{278,279} and a subsequent reaction with lye producing only water as the co-product.⁴⁷⁴ Considering that synthetic natural gas is a widely established concept,²⁸⁰ NaCN is a potentially bio-based carbon source.²⁸¹ Trimethyl orthoformate is accessible by the reaction of sodium methanolate with chloroform, another methane- or methanol-derived chemical (*vide supra*).¹⁸²

The synthesis is not perfectly carbon-atom efficient as atoms are lost in the oxidation process of starting material **302**.

A replacement for NaCN with a non-toxic source for cyanide-anions would be favorable regarding “green” aspects.^{281,475}

2.5.2.3. (–)-Majucin and (–)-jiadifenoxolane A. Maimone *et al.* reported the first synthetic route to complex majucin-type natural products (–)-majucin ((–)-**320**) and (–)-jiadifenoxolane A ((–)-**321**) starting from the abundant feedstock (+)-cedrol ((+)-**304**).^{284,476–479} The synthesis commenced with a Suárez oxidation, followed by a hydroboration/double oxidation



Scheme 51 Use of chiral starting material (+)-cedrol ((+)-304) for the first synthesis of (+)-pseudoanisatin ((+)-333).

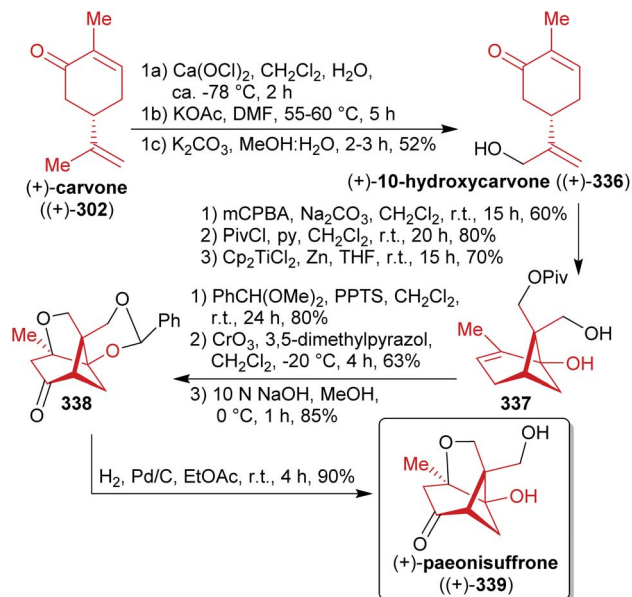


sequence and a NaBH₄ reduction yielding alcohol **316**. The C-4 methine position was oxidized under Suárez conditions to afford ether **317**. Oxidation with *in situ*-generated RuO₄, Riley oxidation and treatment with *L*-selectride led to the tetracyclic enol lactone **318**. The latter was transformed *via* DMDO-oxidation to an α -hydroxyketone, bond reorganization by heating in trifluorotoluene, selective reduction of the α -ketol group using Me₄NBH(OAc)₃ and treatment with acid to furnish the δ -lactone **319**. (–)-Majucin ((–)-**320**) was obtained *via* an enolate oxidation using Vedejs' MoOPH reagent, subsequent epimerization *via* Ru-catalyzed transfer hydrogenation and final dihydroxylation. Majucin (**320**) was converted into (–)-jiadifenoxolane A ((–)-**321**) *via* an intramolecular etherification promoted by regioselective mesylation and nucleophilic displacement (Scheme 49).

Overall, 13 oxidations were employed while three reduction steps were necessary to achieve the correct oxidation state and for stereochemical adjustments. Favorable aspects in the light of “green” chemistry are the use of a photocatalyzed reaction, and of green solvents (acetone, H₂O, MeOH), yet undesired solvents like CCl₄ or PhCF₃ also occur.

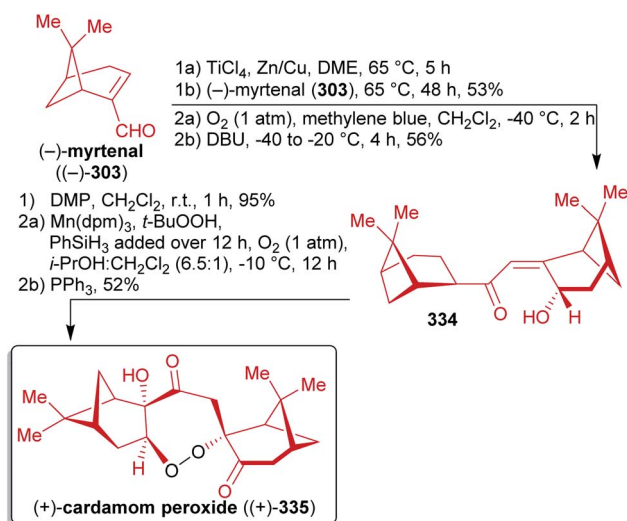
2.5.2.4. (+)-Mikanokryptin. Maimone *et al.* reported the first gram-scale total synthesis of a guaianolide natural product, (+)-mikanokryptin ((+)-**326**). The guaianolides are a major subgroup of sesquiterpene lactones and were investigated from both medicinal and synthetic perspectives.⁴⁸⁰

The synthesis commenced with a one-pot chlorination and Luche reduction of the renewable (+)-carvone ((+)-**302**).^{481,482} This was followed by *O*-silylation and a regioselective ozonolysis of the trisubstituted C=C-double bond. Reductive quenching led to an intramolecular aldol condensation affording enal **322**. The first of two allylation reactions afforded compound **324** and utilized allylic bromide **323**, which can be prepared from wood-based renewable resources methanol and glyoxal furnishing dimethoxyacetaldehyde.^{483,484} The latter can be reacted with methyl acrylate⁴⁸⁵ and subsequently brominated to obtain

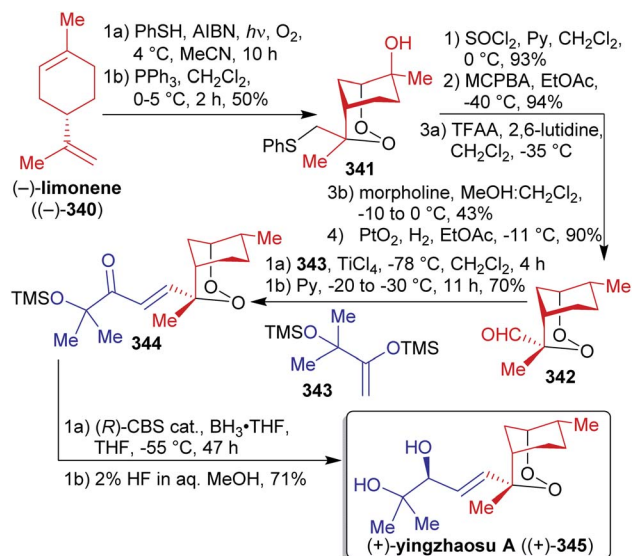


Scheme 53 Synthesis of (+)-paeonisuffrone ((+)-**339**) employing a Ti(III)-promoted epoxide opening and Ti(III)-catalyzed reductive C–C formation as key step.

desired building block **323**.⁴⁸⁰ The dehydration of lactic acid as a cheap and bio-based starting material for acrylic acid is of growing interest and could become a future source for this commodity chemical.^{177–181} With the second (intramolecular) allylation reaction, the seven-membered ring was formed, completing the full guaianolide skeleton **325**. *Via* a reduction using Adams catalyst, subsequent desilylation and allylic oxidation using MnO₂, the natural product (+)-mikanokryptin ((+)-**326**) was obtained (Scheme 50).⁴⁸⁶

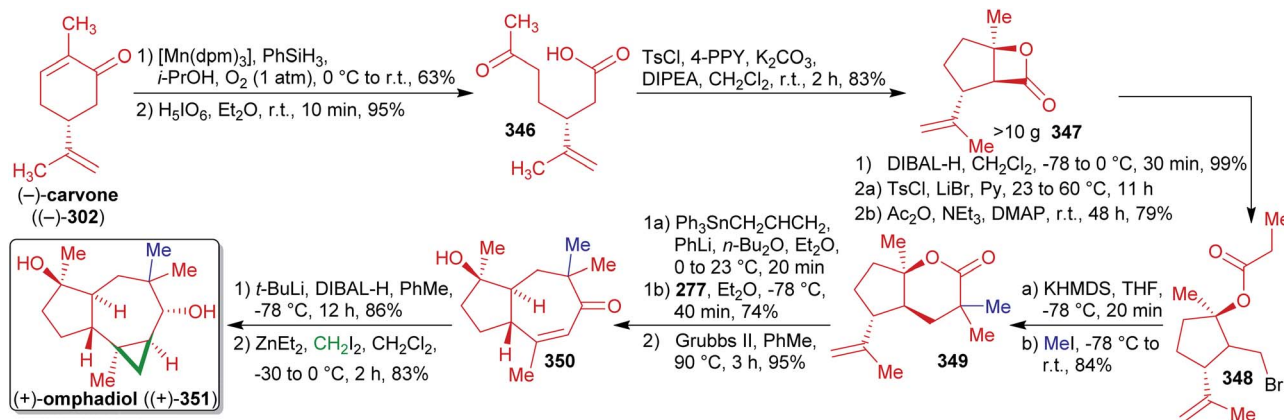


Scheme 52 Synthesis of (+)-cardamom peroxide ((+)-**335**) from (–)-myrtenal ((–)-**303**).



Scheme 54 Synthesis of natural product and antimalarial agent (+)-yingzhaosu A ((+)-**345**).





Scheme 55 Synthesis of (+)-omphadiol ((+)-351) from (-)-carvone ((-)-302). 4-PPY = 4-(1-pyrrolidinyl)pyridine.

2.5.2.5. *(+)-Pseudoanisatin*. In 2016, Maimone *et al.* reported the conversion of sesquiterpene (+)-cedrol ((+)-304), an inexpensive terpene feedstock obtained from biomass,⁴⁸⁷ into the *Illicium*-sesquiterpene (+)-pseudoanisatin ((+)-333).^{488,489}

The synthesis started with the remote oxidation of one of the geminal methyl groups of cedrol (304), methylation and elimination of the formed tetrahydrofuran ring using Meerwein's salt and proton sponge to furnish methoxycedrene 327 (Scheme 51). The C=C-double bond was oxidatively cleaved, lactonization and subsequent lactone hydrolysis, followed by an α -ketol rearrangement then led to compound 329. This crucial intermediate already bears the correct stereochemistry for the final product. Silylation and C-H-oxidation using the terpene-derived homochiral iron catalyst 330 afforded lactone 331.

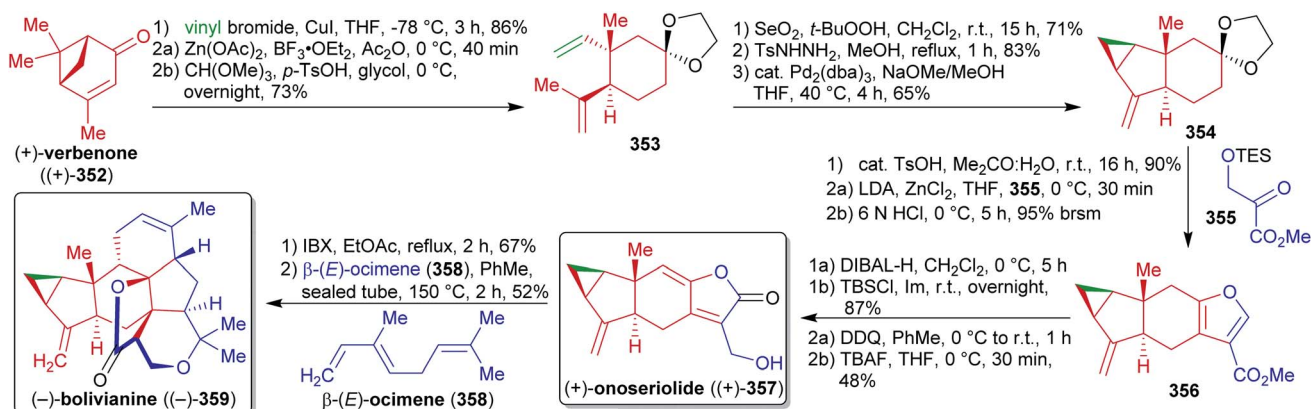
Subsequently, 331 was *O*-ethylated and H_2O eliminated. Through action of *in situ*-formed TMSI, the methyl ether was dealkylated and subsequent treatment with TBAF produced the ϵ -lactone characteristic of pseudoanisatin 333. Dihydroxylation and secondary alcohol inversion completed the enantioselective synthesis of natural (+)-pseudoanisatin ((+)-333).

2.5.2.6. *(+)-Cardamom peroxide*. Starting from natural (-)-myrtenal ((-)-303),⁴⁹⁰ the antimalarial terpene (+)-cardamom peroxide ((+)-335)⁴⁹¹ was obtained in a four-step

synthesis by Maimone *et al.* in 2014 (Scheme 52), proving the absolute configuration of the latter natural product.⁴⁹²

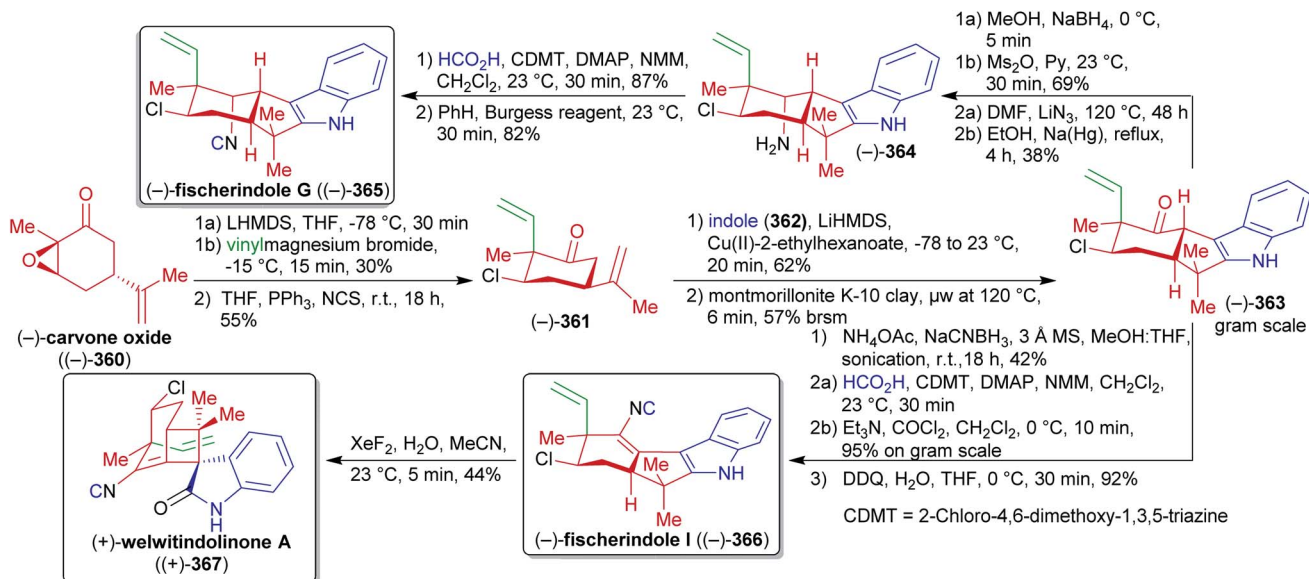
The synthesis started with a McMurry coupling of (-)-myrtenal ((-)-303), affording the dimeric C_{20} carbon skeleton of the final product, followed by a [4 + 2]-cycloaddition with singlet oxygen furnishing enone 334. Subsequent oxidation with DMP and manganese-catalyzed tandem hydroperoxidation completed the synthesis of (+)-cardamom peroxide ((+)-335). Highlights of the synthesis are the high atom-efficiency, the use of molecular oxygen and the application of a photocatalytic reaction.

2.5.2.7. *(+)-Paeonisuffrone*. In 2008, Bermejo *et al.* used (+)-carvone ((+)-302) for the synthesis of the non-natural enantiomer (+)-paeonisuffrone ((+)-339).^{493,494} Natural (+)-carvone ((+)-302) was converted into (+)-10-hydroxycarvone ((+)-336) following a known procedure (Scheme 53).⁴⁹⁵ *Via* epoxidation and protection of the hydroxy function, the subsequent Ti(III)-promoted reaction was enabled. A stereoselective radical cyclization, initiated by reductive epoxide opening, produced triol pivalate 337. The synthesis was completed *via* protection of the diol moiety, an allylic oxidation using CrO_3 and an oxa-Michael addition to the resulting enone to furnish compound 338. A Pd/C promoted reductive deprotection ultimately afforded (+)-paeonisuffrone ((+)-339). The first synthesis of the naturally



Scheme 56 Synthesis of (-)-bolivianine ((-)-359) from (+)-verbenone ((+)-352).





Scheme 57 Synthesis of (-)-fischerindole G ((-)-365) and I ((-)-366) and (+)-welwitindolinone A ((+)-367). CDMT = 2-chloro-4,6-dimethoxy-1,3,5-triazine.

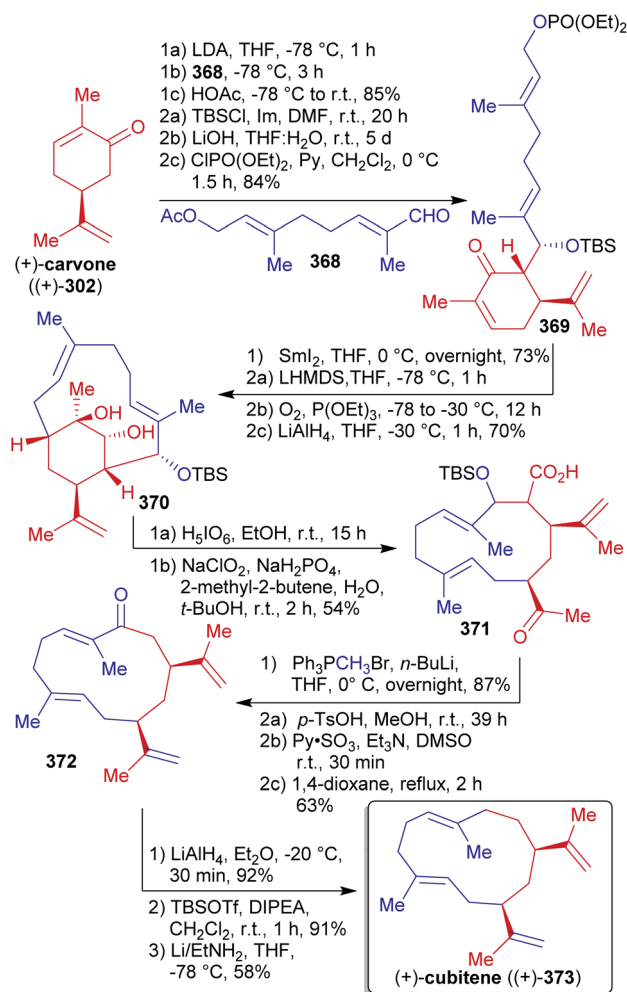
occurring enantiomer, (-)-paeonisuffrone, was published by Hatakeyama *et al.* in 1995.^{494,496}

2.5.2.8. (+)-Yingzhaosu A. The synthesis of the natural product (+)-yingzhaosu A ((+)-345), including the first evaluation of its antimalarial and cytotoxic activities, was reported by Bachi *et al.* in 2005.⁴⁹⁷ The β -sulfenyl endoperoxide **341** was prepared *via* a four component sequential free radical reaction of (-)-limonene ((-)-340) with thiophenol and oxygen, in which five bonds were formed. This was followed by *in situ*-reduction of the formed hydroperoxy group (Scheme 54).⁴⁹⁸ The starting material (-)-limonene ((-)-340) is accessible from biomass.^{499,500} Subsequently, compound **341** was dehydrated, the thioether functionality was selectively oxidized and subjected to a Pummerer rearrangement followed by hydrolysis of the formed hemithioacetal ester, to afford bicyclic aldehyde **342** after hydrogenation of the C=C-double bond.

The second major synthon **343** can be synthesized in three steps from acetone and acetylene (accessible *via* electric arc pyrolysis of methane or from wood-derived charcoal through calcium carbide).⁵⁰¹ First, a reaction to 2-methylbut-3-yn-2-ol is conducted,⁵⁰² followed by oxidation⁵⁰³ and completed by enolization and protection of the afforded hydroxy groups.⁵⁰⁴

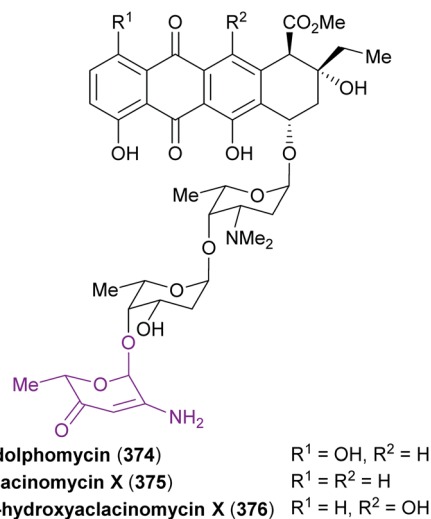
Both synthons were linked through a Mukaiyama aldol reaction followed by *in situ* base-induced dehydration affording the α,β -unsaturated ketone **344**. The synthesis was completed by selective reduction of ketone **344** and acidic workup furnishing the natural product (+)-yingzhaosu A ((+)-345).^{505,506} The obtained product was then subjected to *in vitro* and *in vivo* tests.⁴⁹⁷

2.5.2.9. (+)-Omphadiol. The natural product (+)-omphadiol ((+)-351) was first isolated from the basidiomycete *Omphalotus illudens*⁵⁰⁷ and the first total synthesis was reported by the group of Romo in 2011 (Scheme 55).⁵⁰⁸ The key intermediate in the synthesis of (+)-omphadiol ((+)-351) is bicyclic β -lactone **347**, which was prepared from (-)-carvone ((-)-302).^{452,471,472} The



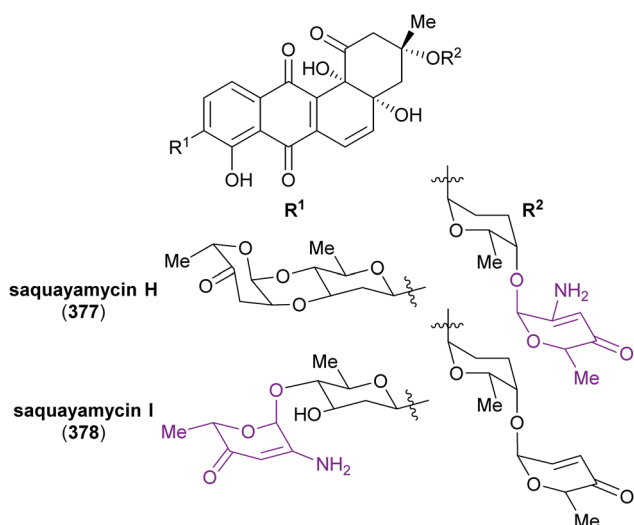
Scheme 58 Synthesis of (+)-cubitene ((+)-373) from (+)-carvone ((+)-302) and geraniol derived aldehyde (**368**).





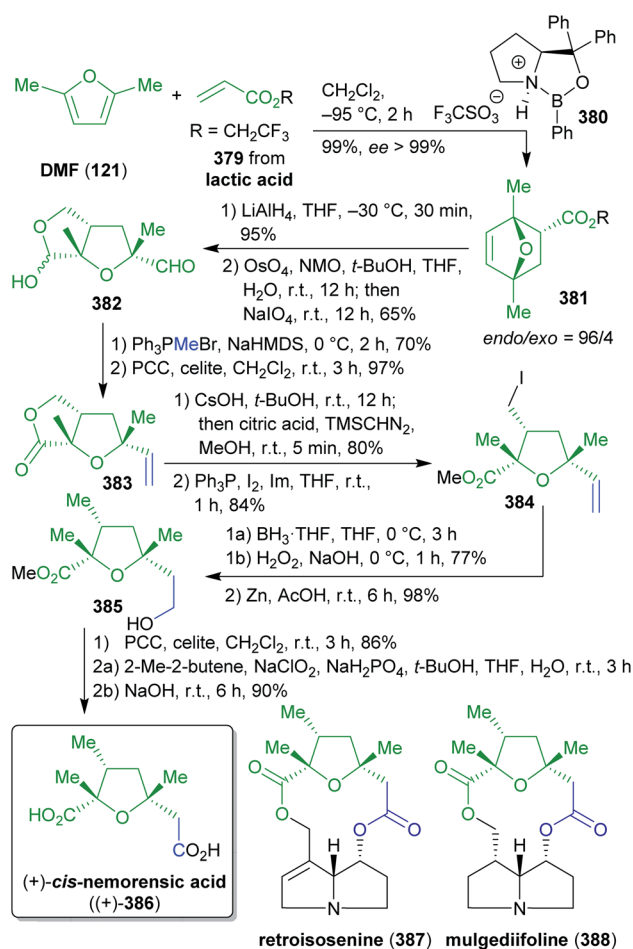
Scheme 59 Tetracycline natural products containing an L-rednose (L-204) moiety.

synthesis commenced with catalyzed hydration of the enone moiety, followed by an oxidative C=C-cleavage. An aldol lactonization afforded bicyclic β -lactone **347**, which was then reduced to the corresponding diol, subjected to a one-pot tosylation/bromination sequence and a subsequent acylation reaction to furnish ester **348**. Treatment with base and iodomethane formed two C–C-bonds in a single operation, affording δ -lactone **349**. With *in situ*-formed allyllithium, a conversion into a ring-opened β,γ -unsaturated ketone was performed and an olefin isomerization/RCM sequence led to cycloheptenone **350**. After reduction and cyclopropanation, the natural product (+)-omphadiol ((+)-**351**) was obtained. Diiodomethane is available from iodoform,⁵⁰⁹ the latter being a product of the well-known reaction from ethanol with I_2 in alkaline medium.³⁰⁰ The synthesis proceeds in a highly efficient manner, using one-pot, sequential and tandem processes, and avoids the use of protecting groups.



Scheme 60 Anthracycline natural products containing an L-rednose (L-204) moiety.

2.5.2.10. (–)-Bolivianine and (+)-onoserialide. In 2013, Liu *et al.* reported the first total synthesis of (–)-bolivianine ((–)-**359**) in 14 steps, including the synthesis of (+)-onoserialide ((+)-**357**).⁵¹⁰ The synthesis commenced with a Michael addition of vinyl reagent **244** to (+)-verbenone ((+)-**352**) (accessible *via* bioconversion of (+)- α -pinene),⁵¹¹ ring-opening of the cyclobutane moiety and formation of 1,3-dioxolane **353** under acidic conditions (Scheme 56). Through Riley oxidation and intermediate preparation of a tosylhydrazone, a diazoalkane was produced, which was subsequently subjected to a metal-catalyzed carbene insertion reaction affording cyclopropane **354**. Acid-catalyzed deprotection enabled the reaction with functionalized pyruvate **355** to afford furan **356**. Building block **355** could be prepared in two steps from natural methyl glycerate by silylation and oxidation.^{510,512} DIBAL-H reduction of furan **356** and modification of the furan ring furnished the natural product (+)-onoserialide ((+)-**357**).^{513–515} By oxidizing the furan moiety, the formed electron-withdrawing group activates the dienophile by decreasing its LUMO energy. This enables a one-pot Diels–Alder/intramolecular hetero-Diels–Alder reaction cascade with natural β -(*E*)-ocimene (**358**)^{516,517} generating three rings, four C–C-bonds, and five stereogenic centers and ultimately furnishing the natural product (–)-bolivianine ((–)-**359**).^{510,518} Vinyl bromide (**244**) can be



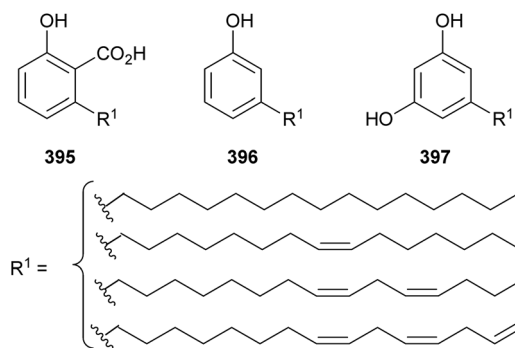
Scheme 61 First asymmetric synthesis of (+)-*cis*-nemorensic acid ((+)-**386**) based on cellulose derived **121**.



prepared from acrylic acid (available from biomass *e.g.* through lactic acid)^{174,177–181} *via* ultrasonically assisted Vilsmeier–Haack reaction.¹⁷⁵ The use of Diels–Alder reactions in the synthesis of natural products is quite attractive against the backdrop of “green” chemistry because of their flawless atom economy. The choice of solvents in the synthesis is exemplary in most cases (acetone, H₂O, EtOAc).

2.5.2.11. *(+)-Welwitindolinone A, (-)-fischerindole I and G.* In 2007, Baran *et al.* were able to synthesize several natural products in a protecting group-free synthesis starting from (-)-carvone oxide ((-)-**360**) (Scheme 57). Intermediate **363** was synthesized on a gram scale by vinylation and chlorination of (-)-carvone oxide ((-)-**360**) affording chloroketone **361**,⁵¹⁹ followed by coupling with indole (**362**) and an acid catalyzed Friedel–Crafts cyclization. Reduction of the ketone, mesylation and nucleophilic substitution with azide, followed by reduction afforded amine **364**. The latter was formylated and dehydrated to furnish the natural product (-)-fischerindole G ((-)-**365**).^{519,520}

Along the other path, a reductive amination of intermediate **363**, followed by formylation, immediate dehydration with phosgene and an oxidation with DDQ in the presence of water led to (-)-fischerindole I ((-)-**366**). In a cascade reaction, the natural product **366** was converted to the spirocyclic, natural product (+)-welwitindolinone A ((+)-**367**).⁵²⁰ The reaction proceeded through electrophilic fluorination of the indole nucleus



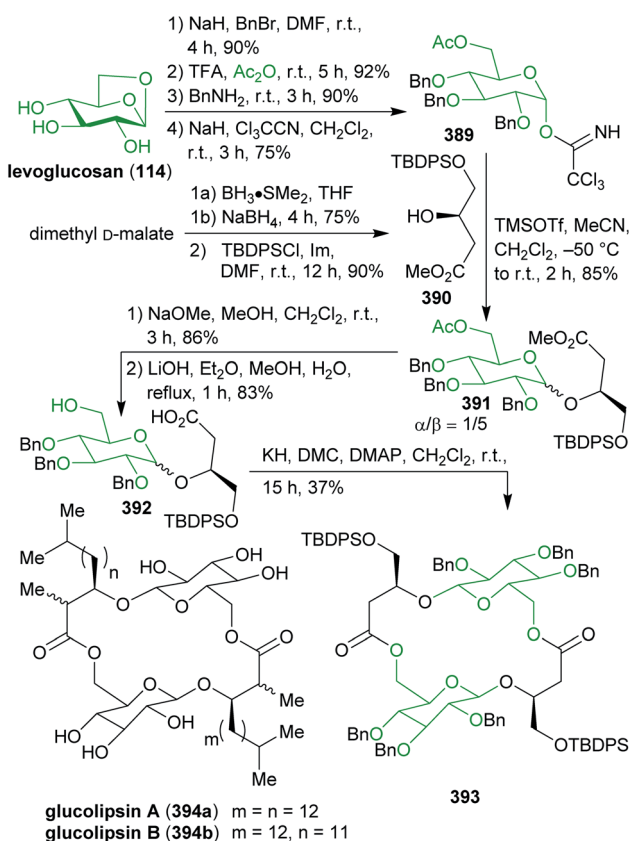
Scheme 63 CNSL constituents: anacardic acid (**395**), cardanol (**396**) and cardol (**397**).

with XeF₂ and trapping with H₂O. Subsequently, fluoride was eliminated and a [1,5]-sigmatropic rearrangement took place.⁵²¹

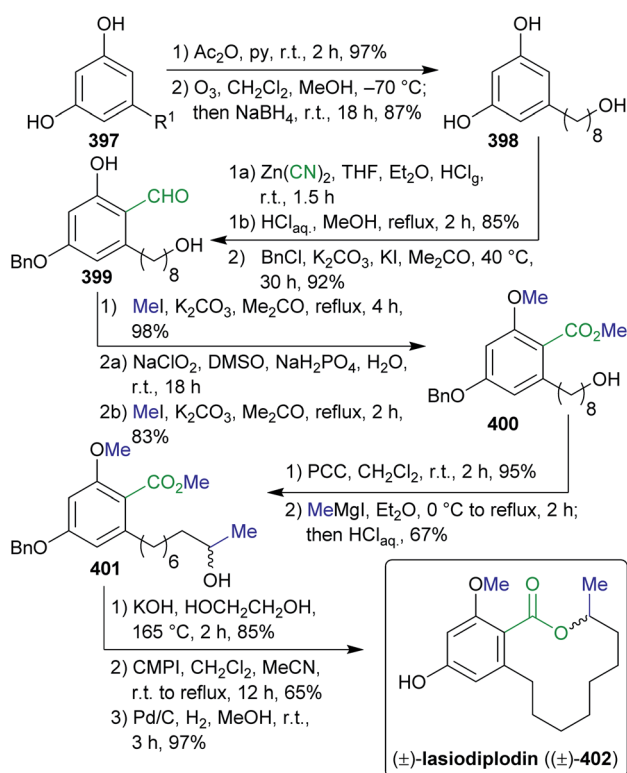
Vinylmagnesium bromide (**71**) can be synthesized from biomass-derived building blocks (*vide supra*). Indole (**362**) can *e.g.* be prepared from tryptophan or from indigo.⁵²² (-)-Carvone oxide ((-)-**360**) can be prepared from (-)-carvone ((-)-**302**).⁵²³

The oxidation states of intermediates gradually escalated over the course of the synthesis with the sole exception of a stereoselective reductive amination.

2.5.2.12. *(+)-Cubitene.* Lindel *et al.* reported an enantioselective total synthesis of the diterpene (+)-cubitene ((+)-**373**).⁵²⁴ (+)-Carvone ((+)-**302**) was reacted first with aldehyde **368** and subsequently *O*-phosphorylated to furnish allyl phosphate **369**



Scheme 62 Synthesis of macrocyclic building block **393** from levoglucosan (**114**) for formal synthesis of glucolipsins **394a, b**. DMC = 2-chloro-1,3-dimethylimidazolium chloride.



Scheme 64 Lasiodiplodin (**402**) synthesis from cardol (**397**).



(Scheme 58).⁵²⁵ By treating the latter with SmI_2 , an intramolecular coupling reaction afforded an [8.2.2]-bicyclic compound, which was converted into an acyloin and subsequently reduced to diol **370**. The latter was cleaved with H_5IO_6 , followed by an oxidation under Pinnick conditions, affording macrocycle **371**. Subsequently, **371** was subjected to a Wittig reaction, followed by deprotection and an oxidation of the hydroxyl group under Parikh–Doering conditions promoting a decarboxylation to ultimately form ketone **372**. A three-step sequence, comprising a reduction of the keto group, silylation of the resulting hydroxy group and an allylic deoxygenation using Li/EtNH_2 , afforded the natural product (+)-cubitene ((+)-**373**).^{524,526}

Aldehyde **368** is available from natural geraniol *via* an allylic oxidation.^{479,527,528}

2.6. Miscellaneous

Since natural products can be very complex molecules and the total synthesis often is already challenging, the construction of the entire carbon framework from bio-based starting materials may constitute a considerable challenge. In addition, it is not always possible to adhere to green synthetic methods and guidelines throughout the entire sequence so that conventional methodology has to be employed where the available eco-friendly alternatives failed. An efficient step in the right direction is the synthesis of fragments and to build at least as much as possible from biomass derived starting materials.

2.6.1. L-Rednose-containing antibiotics. A concise example is the L-rednose (L-**204**) building block synthesized by Sperry and coworkers from 3A5AF (**203**) (Scheme 32).³⁴² It is part of the complex tetracycline-type natural products rudolphomycin (**374**),^{529,530} aclacinomycin X (**375**), 11-hydroxaclacinomycin X (**376**)^{531,532} as well as saquayamycins H (**377**) and I (**378**)^{533,534} which have not been synthesized so far (Schemes 59 and 60). A viable synthesis of an advanced intermediate like **204** based on eco-friendly methods and starting materials already constitutes a significant progress in the total synthesis of these compounds.

2.6.2. (+)-cis-Nemorensic acid. For the synthesis of (+)-*cis*-nemorensic acid ((+)-**386**, Scheme 61), a component of the macropyrrolizidine alkaloids retroisosenine (**387**) and mulge-diifoline (**388**),^{535–540} Ryu and coworkers used 2,5-dimethylfuran (**121**) as the cellulose-derived starting material.⁵⁴¹ Key step of the synthesis was a catalytic enantioselective Diels–Alder reaction with 2,2,2-trifluoroethyl acrylate (only the acrylate portion of which will become part of the product) with excellent *endo*-selectivity using the chiral catalyst **380**. As mentioned earlier, acrylic acid and derivatives are readily available from lactic acid as the bio-based starting material.^{177–181} The carboxylate group of the Diels–Alder product **381** was reduced and after oxidative olefin cleavage, lactol **382** was obtained. Subsequent Wittig reaction with methylphosphonium bromide (accessible from PPh_3 and MeBr) and lactol oxidation furnished lactone **383** with a terminal double bond. The lactone was hydrolyzed, the carboxylic acid esterified and the alcohol was converted into the iodo derivative by means of an Appel reaction. The iodomethylene moiety was

reduced to a methyl group after hydroboration and oxidation of the olefin to furnish **385**. Two step oxidation of the primary alcohol with PCC and Pinnick conditions as well as ester hydrolysis provided enantiopure (+)-*cis*-nemorensic acid ((+)-**386**).

The eco-friendliness of this route is quite favorable regarding the carbon efficiency. Furthermore, almost every carbon atom introduced into the molecule during the synthesis is retained (except for the trifluoroethyl and methyl groups), further increasing the carbon efficiency. Further circumstantial protecting group operations are completely avoided.

2.6.3. Macrolide precursor for glucolipin synthesis. In 2003, Cleophax and coworkers utilized cellulose-derived **114** and dimethyl malate for the synthesis of the macrocyclic moiety **393**⁵⁴² which could be converted into the antibiotic glucolipins (**394a–b**, Scheme 62)⁵⁴³ and cycloviracins (not shown).^{544–547} Although a number of total and formal syntheses which also use bio-based starting materials in the form of *e.g.* glucose⁵⁴⁷ have been published,^{548–553} we chose this work to showcase the value of levoglucosan as a less common starting material.

After benzyl protection, **114** was transformed into the monocyclic trichloracetimidate **389**, which was reacted with the dimethyl D-malate-derived building block **390** in a Schmidt glycosylation. Both ester groups were saponified and subsequent ring forming esterification furnished **393**.

This approach makes exemplary use of enantiopure bio-based starting materials to furnish a pivotal building block for the syntheses of fairly complex natural products, but is hampered by extensive protecting group usage well known from carbohydrate chemistry.⁵⁵⁴

2.6.4. (±)-Lasiodiplodin from Cashew Nut Shell Liquid (CNSL). A highly promising renewable feedstock, although rather unusual for natural product synthesis, is cashew nut shell liquid, a waste product of the cashew nut production and is the cold ethanol extract of the waste shells. It contains in up to 95% the three phenolic compounds anacardic acid (**395**), cardanol (**396**) and cardol (**397**) which all carry a C_{15} chain with one to three double bonds (Scheme 63).⁵⁵⁵ This unique moiety in combination with the origin from a waste stream of food production makes it the ideal renewable resource.^{556–559} The for natural product synthesis, the long alkyl/alkenyl chain is rather impractical but CNSL has found numerous applications in fuel research,⁵⁶⁰ polymer chemistry,^{561–563} synthesis of fine chemicals^{564–566} and for the synthesis of functional materials like surfactants^{567,568} and UV absorbers.^{116,569}

Magalhães and dos Santos⁵⁷⁰ managed to utilize CNSL-derived cardol (**397**) for the synthesis of antileukemic lasiodiplodin (**402**).^{571,572} Acetyl protected cardol was subjected to ozonolysis and following reductive treatment to yield a truncated alcohol (Scheme 64).

After saponification of the acetates, formylation was performed by means of a Gattermann reaction and the *p*-hydroxy group was benzylated to furnish aldehyde **399**. The second aromatic hydroxy group was converted to the methyl ether and aldehyde oxidation was achieved under Pinnick conditions. The respective carboxylic acid was *O*-alkylated with iodomethane



and the remaining primary hydroxy group was oxidized to an aldehyde, which was subjected to a Grignard reaction with methylmagnesium iodide to yield secondary alcohol **401**. After saponification and macrolactone formation through the action of 2-chloro-1-methylpyridinium iodide (CMPI), the benzyl group was cleaved to furnish racemic lasiodiplodin.

Although this very concise approach makes formidable use of this particular starting material, it also demonstrates an issue when used for total synthesis: The C₁₅ moiety often has to be truncated so that a non-negligible part of the molecule (in this case about one third) is not retained in the desired final product. Therefore, the carbon and atom efficiency is decreased – however, the C₇-fragment split off may *e.g.* find application in the synthesis of the fragrance jasmin aldehyde.⁵⁷³

3. Future challenges and outlook

The use of fossil carbon sources as the basis of the vast majority of current activities in synthetic organic chemistry is only rarely questioned by practitioners and scholars. Nevertheless, the current discussion on the necessity of CO₂ reduction and the size of the doubtlessly finite underground deposits of fossil carbon brings up interesting challenges for current and future chemists. Atom awareness among the chemical community, *i.e.* the knowledge of the origin of the matter that we deal with in our work, certainly leaves some room for improvement. As outlined in the Introduction, chemists were never shy to accept new challenges, *e.g.* to utilize the seemingly unattractive, black and smelly coal tar to produce beautiful dyestuffs or life-saving drugs. The combination of starting materials from renewable feedstocks with eco-friendly solvents, reagents, and methodologies as well as a reduced energy consumption can ultimately lead to processes with minimal impact on our ecosystem. Therefore, existing methods, synthetic routes and processes need to be revisited constantly. A big part of whether or how quickly those concepts will be applied on a large scale is dependent on the economic competitiveness.

Furthermore, the conception of bio-based starting materials has also reached other organic chemical fields like pharmaceutical and agrochemistry. The synthesis of the anti-ulcer drug ranitidine⁵⁷⁴ and the insecticide prothrin from CMF (**120**)⁵⁷⁵ as well as the synthesis of norfenefrine and fenoprofen from cashew nut shell liquid-derived cardanol⁵⁷⁶ are pioneering examples of this development.

Another attractive trend in organic chemistry in terms of sustainability is the conception of protecting group free sequences^{577–580} as already demonstrated for the synthesis of fischerindole G (**365**) and I (**366**) as well as of welwitindolinone A (**367**) (Scheme 57).^{521,577–580} This could particularly influence natural product synthesis, a field in which the extensive use of protecting group transformations is commonplace. Atom- and step-efficiency of synthetic routes could be significantly increased if alternative methods for achieving selectivity can be employed instead.

4. Conflicts of interest

There are no conflicts of interest to declare.

5. Acknowledgements

We thank the members of the STANCE consortium for helpful discussions.

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