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Recent advancements in synthetic methodologies of 3-substituted phthalides and their application in the total synthesis of biologically active natural products

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We have provided a critical review that focuses on key developments in the area of 3-substituted phthalides and their role in the development of important biologically active natural products. 3-Substituted phthalides are vital molecules owing to their fascinating biological activity. The scope, isolation, and characterization of various naturally occurring racemic and chiral 3-substituted phthalides have been covered. We have put significant emphasis on recently developed research methodologies for the synthesis of racemic and chiral 3-substituted phthalides. These newer approaches are essential for the development of newer and elegant strategies for the synthesis of phthalide-based or similar molecular architecture with broader substrate scope and higher stereoselectivities. Also, we have discussed the application of 3-substituted phthalides as a precursor for the synthesis of natural products and their analogs.

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1. Introduction

One of the prime areas of research in organic chemistry has been concerned with the development of small-molecule natural products. A considerable number of modern-day drug developments are inspired by various sets of natural products, such as amino acids, flavonoids, alkaloids, terpenoids, quinonoid, and steroids.[1] This area of research has paved the way for an important class of chemistry, known as medicinal chemistry.

An extensive series of biologically important natural products consist of phthalide frameworks.[2] Phthalides are a prominent branch of natural products due to their biological

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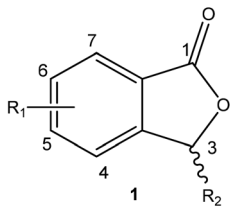

Fig. 1 1(3*H*)-Isobenzofuranones **1** (phthalides) and their derivatives.

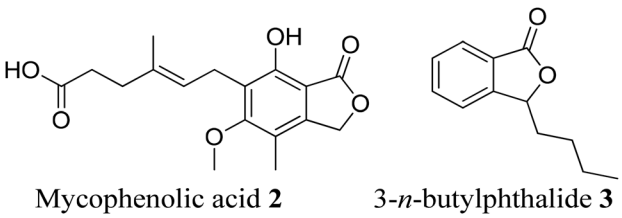

Fig. 2 Structure of mycophenolic acid **2** and 3-*n*-butylphthalide **3**.

importance. The fundamental core structure of phthalide consists of a benzene ring fused with a γ-lactone between carbons 1 and 3 (Fig. 1). All the known phthalide compounds have been recognized as derivatives of 1(3*H*)-isobenzofuranone. Mainly, phthalides have been found commonly in plant genera and also in fungi, bacteria, and liverworts.

More than 180 naturally occurring phthalide derivatives have been identified. Among them, nearly 140 phthalides were isolated from a wide variety of plant species. These isolated phthalides have shown a broad spectrum of important clinical properties, such as anti-platelet accumulation, anti-smooth proliferation, anti-thrombosis, protection against cerebral ischemia, anti-angina, and cardiac function modulation and actions on the central nervous system.[3]

In ancient times, many phthalide-containing plants were used as herbal medicines. In China, phthalide-containing herbs have been recognized as some of the most commonly used natural medicines in traditional medicinal practice. Rhizoma Chuanxiong (Chinese name Chuanxiong) and Radix *Angelicae sinensis* (Chinese name Danggui) have been used for the treatment of cerebral- and cardiovascular diseases and female irregular menstruation for more than 2000 years.[4]

Phthalide containing drugs have gained worldwide popularity because of the wide range of pharmacophore activities of the moiety.[5] For example, a significant problem during organ transplantation is a rejection of the transplanted organ. Mycophenolic acid (mycophenolate) **2** is a phthalide-containing immunosuppressant drug given to facilitate organ transplantation. It was the first antibiotic synthesized in a pure crystalline state. The US Food and Drug Administration has also approved this for use in kidney transplantation.[6] Similarly, *n*-butylphthalide (NBP) **3** also became a successful anti-platelet drug for ischemia-cerebral apoplexy[7] (Fig. 2). The Chinese government had approved this as an anti-ischemic stroke drug in 2002. Taking these facts into consideration, we can state that phthalide moiety has been used as a valuable framework in synthesizing many pharmaceutical drugs.[5]

Some phthalide-containing natural products are also reported in the literature. Phthalide plays a vital role as a building block[8] in the synthesis of many natural products. For example, fuscinarin **4** is a potent human CCR5 antagonist, used to block the entry of HIV into host cells.[9] However, the bioactivities of

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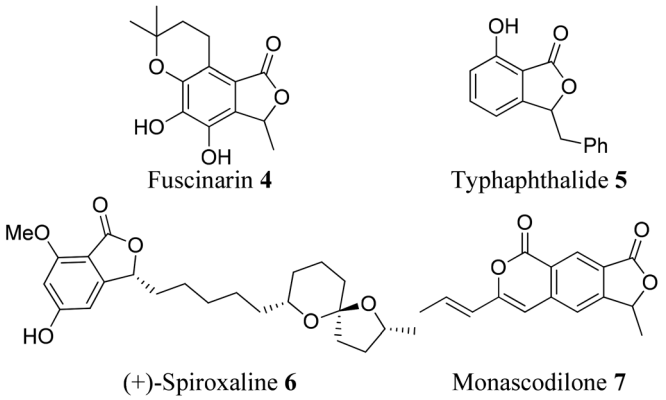


Fig. 3 Naturally occurring 1(3*H*)-isobenzofuranones **4–7**.

(−)-typhaphthalide **5**,[10] (+)-spiroxaline **6**,[11] and monascodilone **7**[12] are still not known (Fig. 3).

There are several available reactive sites of phthalides which have been explored, *i.e.*, a nucleophilic attack on C_1 carbonyl group, nucleophilic substitution reactions at C_3 position carbanion, and reactions on the C_4, C_5, C_6 and C_7 positions of the phthalide.[13] The 1(3*H*)-isobenzofuranone was initially synthesized in 1922 by Perkin and coworkers, *via* thermal decomposition of ethyl 2-(bromomethyl)benzoate.[14] Later in 1955, Eliel and coworkers performed the reduction of methyl phthalate to phthalide in good yield using $LiAlH_4$.[15] In 1989, Watanabe and coworkers utilized a Diels–Alder reaction between substituted furanones and silyloxydienes to provide substituted phthalides in moderate to excellent yields.[16] Recently, directed *ortho*-metallation, the reaction between homophthalic anhydride and benzil,[17] the Heck–Matsuda reaction,[18] and many more methods have been introduced to synthesize substituted phthalides.

1.1 Scope for 3-substituted phthalides

As we have already discussed, phthalide moiety is present in many natural products. Phthalides that are substituted at the C-3 positions possess an extensive range of biological and physiological activities.[19] This moiety has been an essential intermediate to synthesize versatile natural products.[20] This fact has led extensive efforts in the field of 3-substituted phthalides in the past two decades[18] (Fig. 4). Different synthetic methodologies of selected natural products using 3-substituted phthalides as intermediates are described in the later part of the review.

Statistically, more than 60% of the drugs currently available on the market are chiral molecules. As a result, asymmetric synthesis of chiral phthalides introducing C-3 chirality has also achieved considerable attention.[21] Subsequently, an extensive number of asymmetric synthetic methodologies have been established for a variety of naturally occurring molecules with the potential treatment of different kinds of diseases.

The attention of this review is primarily on the synthesis and reactivity of the active methylene compounds, *i.e.*, 1(3*H*)-isobenzofuranones. Previously, Mal *et al.* and Renoux *et al.* published two excellent reviews on the chemistry of phthalides.[5,19]

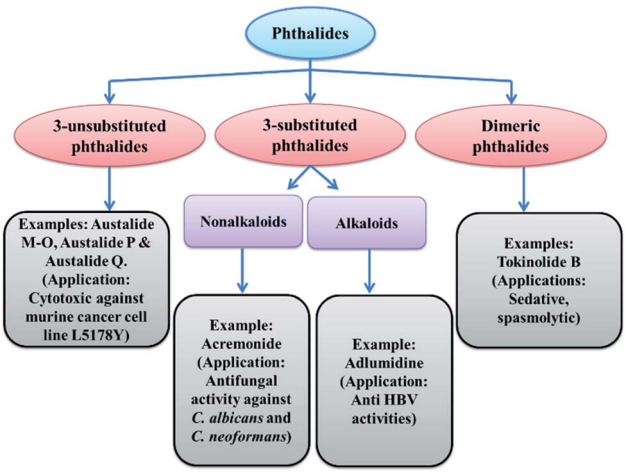


Fig. 4 Classification of phthalides and their examples.

However, as per our knowledge, in previous literature reviews, the chemistry of racemic and chiral 3-substituted 1(3*H*)-isobenzofuranones and its application in total synthesis of important natural products was not discussed in detail. In this review, the synthetic methodologies for racemic and chiral 3-substituted 1(3*H*)-isobenzofuranones are discussed with particular emphasis on recent advances. Also, the application of racemic and chiral 3-substituted 1(3*H*)-isobenzofuranones as precursors for the synthesis of other critical molecular moieties are discussed.

The work presented here can benefit researchers in developing newer efficient strategies. This review paper contributes to ongoing efforts in seeking to develop and expand the utility of 3-substituted phthalides as precursors for much broader objectives.

1.2 Sources of a different kind of phthalides

Plants, fungi, bacteria, and liverworts have been different sources for phthalides. More than 180 naturally occurring phthalides appear in the literature. Most of these (~137) are extracted from 202 diverse species of plants; as a result, phthalide-containing plants were long used as herbal medicines.[22] Most naturally occurring phthalides are obtained from two plant species, *Ligusticum* and *Angelica*, in the Umbelliferae family. Some of the isoquinoline type phthalides such as noscapine **8** and bicuculine **48** are isolated from the poppy family. From the genus *Ligusticum*, more than 53 naturally occurring phthalides have been isolated from *Ligusticum*, and 38 biologically phthalides have been isolated from *Angelica*.[20,23]

1.3 Extraction, isolation, and characterizations of phthalides

The extraction of naturally occurring biologically active phthalides is one of the critical steps of analysis. It involves techniques such as pre-washing, grinding, and drying of plant materials to obtain a homogenous sample. It should be taken care that potential plant constituents are not degraded during

Table 1 Important biologically active natural products encompassing 3-substituted phthalide framework

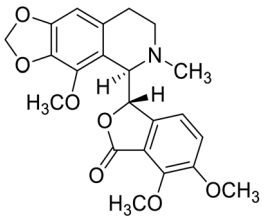
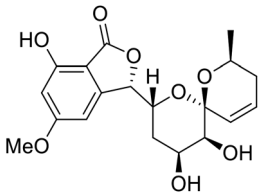
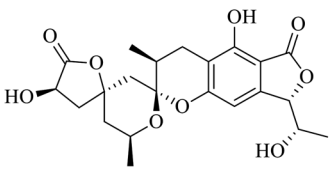
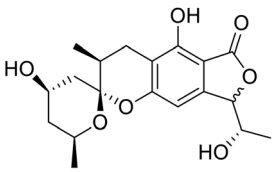
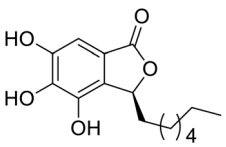
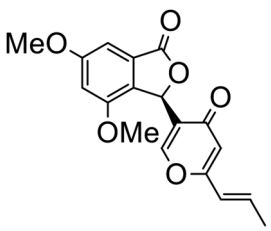
S. no.	Natural products	Isolation sources	Biological activities
1 (ref. 30)	 Noscapine **8**	Cultivated opium poppy plants	Anti-tussive, anti-cancer, and potential antineoplastic activities
2 (ref. 31)	 (+)- Aigialospirol **9**	*Aigialus parvus* BCC 5311	Not known
3 (ref. 32)	 Virgatolide A **10**	*Pestalotiopsis virgatula*	Cytotoxic against HeLa (cervical epithelium) cells
4 (ref. 17)	 (i) Virgatolide B (C3 = α) **11** (ii) Virgatolide C (C3 = β) **12**	*Pestalotiopsis virgatula*	Cytotoxic against HeLa (cervical epithelium) cells
5 (ref. 33)	 Cytosporone E **13**	*Cytosora* sp. CR200	Anti-microbial
6 (ref. 34)	 Vermistatin **14**	*Penicillium vermiculatum* DANG	Cytotoxic against tumor cells

Table 1 (*Contd.*)

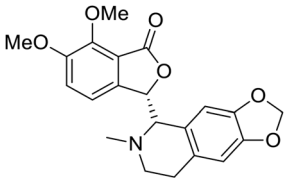
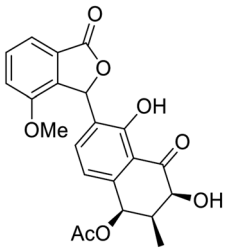
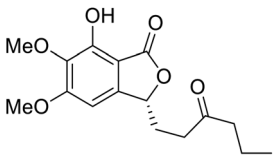
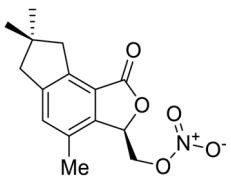
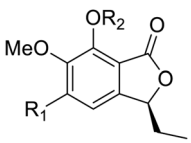
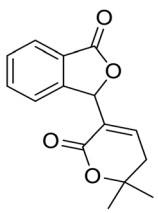
S. no.	Natural products	Isolation sources	Biological activities
7 (ref. 35)	 (-)-Hydrastine **15**	*Corydails stricta*	Anti-paclitaxel – resistant anti-cancer (ovarian) activity
8 (ref. 36)	 Rubiginone **16** (Stereochemistry at C-3 position unknown)	*Streptomyces* sp.	Anti-bacterial activity, prevents the growth of specific Gram-positive bacteria and cytotoxic against diverse tumor cells
9 (ref. 37)	 Colletotrialide **17**	*Collectotrichum* sp.	Anti-oxidant and chemo preventive properties
10 (ref. 38)	 Alcyopterosin E **18**	*Alcyonium paessleri*	Cytotoxicity toward human larynx carcinoma
11 (ref. 39)	 (i) $R_1 = R_2 = H$ **19** (ii) $R_1 = OMe$, $R_2 = H$ **20** (iii) $R_1 = OMe$, $R_2 = Me$ **20**	*Pittosporum illicioides*	*In vitro* inhibitory activity on neutrophil pro-inflammatory response
12 (ref. 40)	 Catalpalactone **22**	*Catalpa ouata* G.	Anti-tumor promoting activity

Table 1 (*Contd.*)

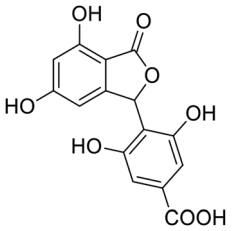
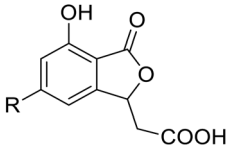
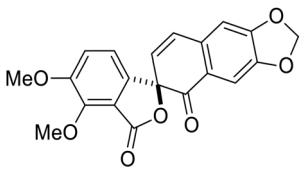
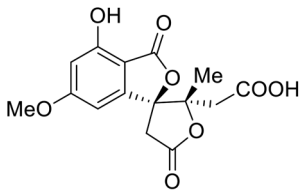
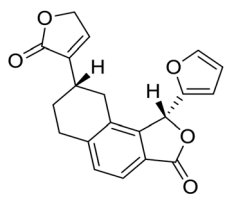
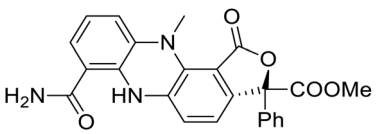
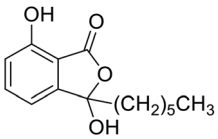
S. no.	Natural products	Isolation sources	Biological activities
13 (ref. 41)	 Cryphonectric acid **23**	*Cryphonectria parasitica*	Anti-fungal activity, (inhibits the formation of tomato seedings)
14 (ref. 42)	 R = H, Isoochracinic acid **24** R = OH, Herbaric acid **25**	*Alternaria kikuchiana* (isoochracinic acid), *Cladosporium herbarum* (herbaric acid)	Anti-bacterial and anti-biotic
15 (ref. 43)	 (-)-Arnottin II **26**	*Xanthoxylum arnottianum*	Not known
16 (ref. 44)	 Altenuic acid **27**	*Alternaria tenuis*	Not known
17 (ref. 45)	 Tilifodiolide **28**	*Salvia tiliaefolia* and *Salvia puberula*	Plant growth stimulator
18 (ref. 46)	 Dermacozine D **29**	*Dermacoccus abyssi*	Cytotoxic against different tumor cells lines
19 (ref. 47)	 Corollosporine **30**	*Corollospora maritima*	Anti-bacterial activity against *Staphylococcus*

Table 1 (*Contd.*)

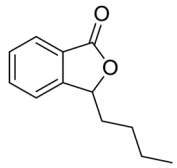
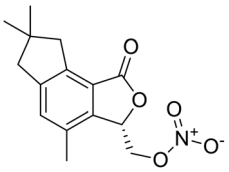
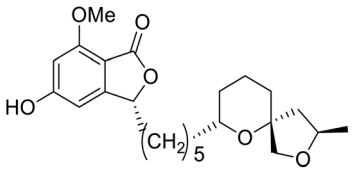
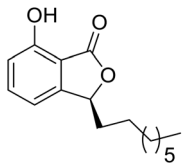
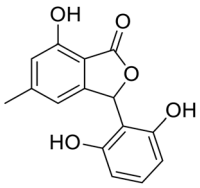
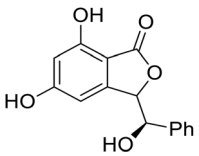
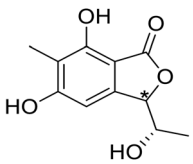
S. no.	Natural products	Isolation sources	Biological activities
20 (ref. 48)	 *n*-Butylphthalide **2**	*Apium graveolens*, *Angelica sinensis*	Anti-convulsant, anti-stroke and anti-proliferative
21 (ref. 49)	 Alcyopterosin E **31**	Subantarctic soft coral *Alcyonium paessleri*	Toxic towards Hep-2 (human larynx carcinoma) cell line
22 (ref. 50)	 (+)- Spirolaxine **6**	Fungus *Sporotrichum laxum*	Anti-tumor and active against *Helicobacter pylori*, also, lower the cholesterol level in the body
23 (ref. 51)	 Paecilocin A **32**	Fungus *Paecilomyces variotii*	Anti-bacterial activity against pathogenic bacteria including *Staphylococcus aureus* 3089 and *Vibrio parahaemolyticus* 7001
24 (ref. 52)	 Isopestacin **33**	*Pestalotiopsis microspora*	Anti-fungal activity
25 (ref. 53)	 Matteucen C **34**	Chineses medicinal herb *Matteuccia orientalis* for the treatment of hemostatics and reliving ostalgia	Not reported
26 (ref. 54)	 (3S)- Pestaphthalides A **35a** (3R)- Pestaphthalides A **35b**	Solid culture of an isolate of *Pestalotiopsis foedans*	Anti-fungal

Table 1 (*Contd.*)

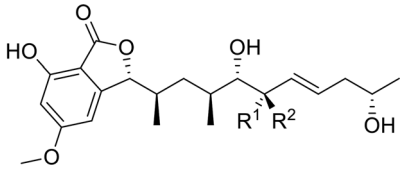
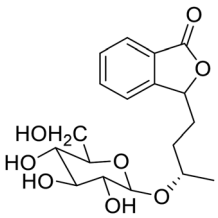
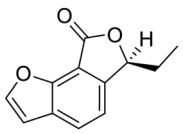
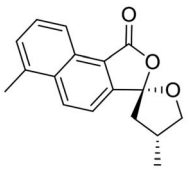
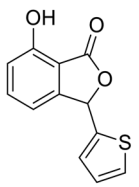
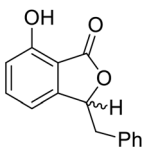
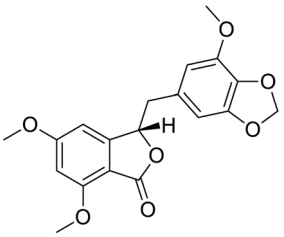
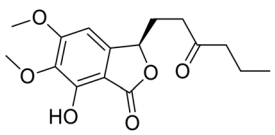
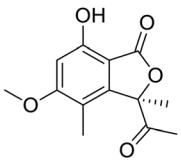
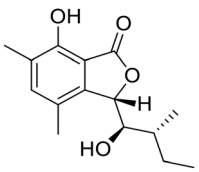
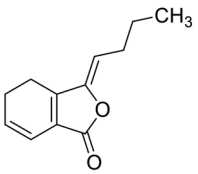
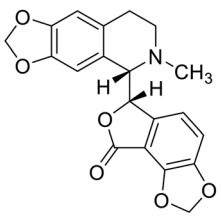
S. no.	Natural products	Isolation sources	Biological activities
27 (ref. 55)	 Paecilomycin C (R^1 = H, R^2 = OH) **36** Paecilomycin D (R^1 = OH, R^2 = H) **37**	Solid culture of *Paecilomyces* sp. SC0924	Anti-fungal
28 (ref. 56)	 Celephthalide A **38**	Celery seed	A diuretic for bladder and kidney complaints and adjuvant in arthritic conditions
29 (ref. 57)	 Concentricolide **39**	Ascomycete *Daldinia concentrica*	Anti-HIV-1
30 (ref. 58)	 Danshenspiroketallactone **40**	Traditional Chinese medicine consisting of *Salvia miltiorrhiza*	Immunosuppressants and anti-stroke
31 (ref. 59)	 Chrycolide **41**	Leaves and stem of a popular vegetable *Chrysanthemum coronarium*	Anti-feeding activity
32 (ref. 60)	 Typhaphthalide **42**	Rhizomes of *Typha capensis*	Anti-bacterial activity against diarrhea and dysentery

Table 1 (*Contd.*)

S. no.	Natural products	Isolation sources	Biological activities
33 (ref. 61)	 3a- [4'- Methoxy-4',5'-methyllenedioxybenzyl]-5,7-dimethoxyphthalide **43**	*Frullania* sp.	Cytotoxic against human promyelocytic leukemia
34 (ref. 62)	 Colletotrialide **44**	*Euryops hebecarpus*	Not known
35 (ref. 63)	 (*R*)-3-acetyl-7-hydroxy-5-methoxy-3,4-dimethylisobenzofuran-1(3*H*)-one **45**	*Endophytic fungus*	Anti-oxidant activity
36 (ref. 64)	 Chrysoarticulin C **46**	*Leptosphaeria* sp.	Anti-fungal activity
37 (ref. 65)	 Z-Ligustilide **47**	*Ligusticum porteri*	Anti-proliferative activity (sedative and relaxant)
38 (ref. 66)	 (+)- Bicuculine **48**	*Fumaria capreokzta* L and *Fumaria bella*	Potent GABa receptor antagonist and used to block Ca^{2+} activated potassium channels

extraction. The selection of solvent also plays a crucial role in the extraction of phthalides, and it largely depends upon the nature of the phthalides. Most phthalides are non-polar, so for the extraction of such molecules, hexane or petroleum ether can be used as an initial extraction solvent. To extract polar phthalides, we use polar solvents, such as ethanol, chloroform,

methanol, and ethyl-acetate.[21,24] The extraction process for phthalides has remained mostly unchanged over the years; however, some upgraded extraction procedures have been reported.[25,26]

Phthalides are usually isolated *via* column chromatography, thin layer chromatography (TLC), and HPLC, with column chromatography being the most common. Silica, alumina, and LH-20 are frequently used adsorbents for column chromatography.[27,28] Other techniques that have been used for some specific phthalides include preparative TLC (PTLC), centrifugal circular TLC (CCTLC), medium-pressure liquid chromatography (MPLC), high-speed countercurrent chromatography (HSCCC), droplet-countercurrent chromatography (DCCC), and high-vacuum low-temperature distillation.[29]

Initially, the characterization of naturally occurring phthalides was carried out through melting points, boiling points, saponification, UV spectroscopy, and hydrolysis techniques. After the development of NMR, IR, GC-MS, and X-ray crystallography, characterizing phthalides has become much easier.

2. Isolated natural products encompassing 3-substituted phthalide framework

Table 1 summarises examples of isolated natural products encompassing 3-substituted phthalide framework

3. Synthetic routes for 3-substituted 1(3*H*)-isobenzofuranones

We have classified synthetic routes to access 3-substituted (±)-1(3*H*)-isobenzofuranones in two major titles. First, we have emphasized recent approaches to generate racemic 3-substituted (±)-1(3*H*)-isobenzofuranones, and later we have described recent approaches to generate optically pure 3-substituted 1(3*H*)-isobenzofuranones.

3.1 Recent methodologies for the synthesis of 3-substituted (±)-1(3*H*)-isobenzofuranones

3.1.1 Metal catalyzed synthesis of 3-substituted (±)-1(3*H*)-isobenzofuranones. Fan and co-workers[67] have reported 3-substituted phthalides **51** *via* a ruthenium-catalyzed intermolecular cascade reaction of aromatic acids **49** with aromatic aldehydes **50**. The synthesis involves the direct insertion of the C–H bond of the aromatic acids into a polar C=O bond of aromatic aldehydes, which is followed by the consecutive intramolecular nucleophilic substitution. The polarity (electrophilicity) of the C=O bond in aromatic aldehydes was increased by having electron-withdrawing groups (NO_2, CF_3, F, Cl, Br) on the aromatic ring (Scheme 1).

Nguyen and co-workers[68] demonstrated a direct route to obtain phthalides **53** *via* carboxylation of benzoxasiloles **52** with carbon dioxide, using CuI as a catalyst. Several advantages of this methodology are the use of copper salt as a catalyst, economical starting materials and convenient reaction setup (Scheme 2). The main challenge of this methodology was the unexplored reactivity of organosilanes with CO_2.

Arcadi and co-workers[69] have described a palladium-catalyzed hydroarylation and hydrovinylation reaction of γ-propargylic alcohols **54** with aryl iodides **55** to afford crude γ,γ-disubstituted allylic alcohols **56**. Allylic alcohols **56** were treated with NaOH followed by acidification afforded 3,3-disubstituted phthalides **59** in good to moderate yields (Scheme 3).

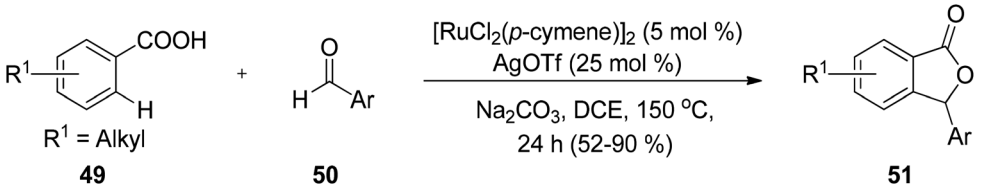
Matsuda and co-workers[70] described an oxidative cyclization of phthalaldehydes **60** and alcohols catalyzed by rhodium(III) catalyst and copper acetate to afford 3-alkoxyphthalides **61** in good to moderate yields (Scheme 4). The reaction is believed to be proceeding *via* Rh–Cu relay catalytic system.

The work was further extended to explore the utility of 1,3-dicarbonyl compounds **63** as nucleophiles for the reaction with phthalaldehydes **62** under similar conditions. This led to the synthesis of 3-alkylphthalides **64** in excellent yields (Scheme 5).

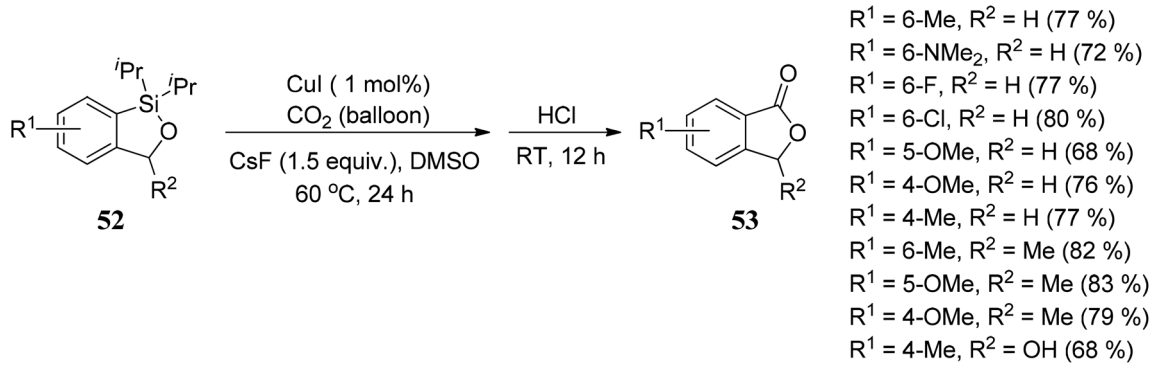
Gandeepan and co-workers[71] demonstrated rhodium(III)-catalyzed regio- and stereoselective synthesis of disubstituted *E*-phthalides **67** from aryl acids **65** and allenes **66**. The reaction proceeded *via ortho* C–H bond activation followed by an annulation pathway. The scope of the methodology was further investigated on a variety of aryl acids **65** and allenes **66** (Scheme 6).

3.1.2 Hydroiodination-triggered synthesis of 3-substituted (±)-1(3*H*)-isobenzofuranones. Hydroiodination-triggered cascade reaction is demonstrated by Kawaguchi and co-workers[72] by using I_2, PPh_3, and H_2O in $CDCl_3$ to furnish 3-substituted phthalides **69** in excellent yields. The reaction proceeds *via* a four-step sequence, *i.e.*, desilylation, hydroiodination, cyclization, and reduction, in one pot (Scheme 7). The present method eliminates the need for a metal catalyst to form phthalides.

The substrate scope of 2-ethynylbenzoates **70** was also studied by using cyano, chloro, phenyl, and ester groups on the side chain. They were tolerated during the four-step sequence to provide 3-substituted phthalides **71** (Scheme 8).



Scheme 1 Ruthenium catalyzed the synthesis of 3-substituted phthalides.



Scheme 2 Synthesis of benzoxasiloles *via* copper-catalyzed direct carboxylation.

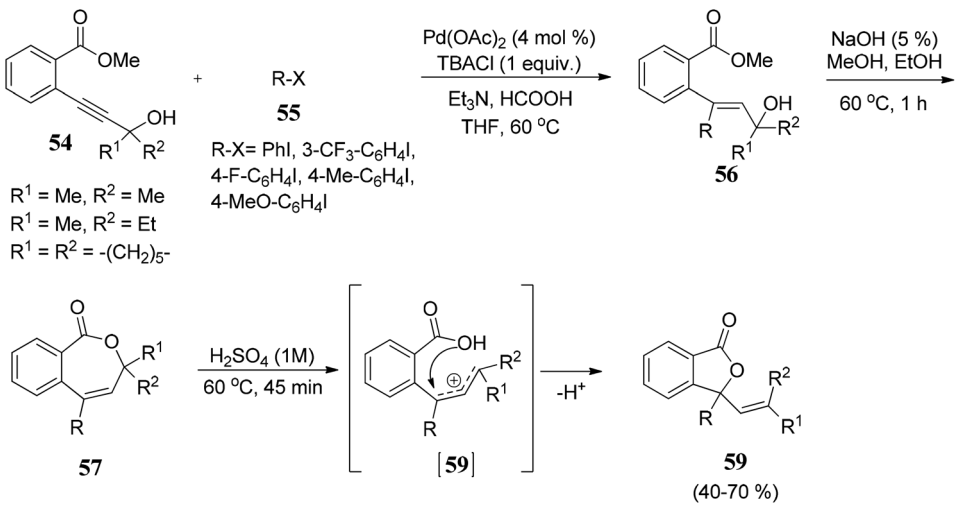
3.1.3 Synthesis of 3-substituted (±)-1(3*H*)-isobenzofuranones using β-keto acids as a nucleophile center. Jia and co-workers[73] developed a one-pot cascade aldol/cyclization reaction of **72** wherein β-keto acids **73** were directly employed as a nucleophilic center, and glycerol was used as a solvent. Here, β-keto acids functioned as ketone enolate equivalents. An extensive substrate scope for β-keto acids was explored, affording a wide variety of 3-substituted phthalides in good to excellent yields (Scheme 9).

3.1.4 Synthesis of 3-substituted (±)-1(3*H*)-isobenzofuranones using Schiff base. Perillo and co-workers[74] developed cascade reaction of glycine Schiff base **77** with 2-carbomethoxy benzaldehyde **76**, which involved aldol condensation followed by cyclization under the acidic conditions to provide α-amino ester 3-substituted phthalides **80** in good yield (Scheme 10). The methodology was further extended to develop an enantioselective version of the reaction to obtain chiral 3-substituted phthalides in high ee's.[73]

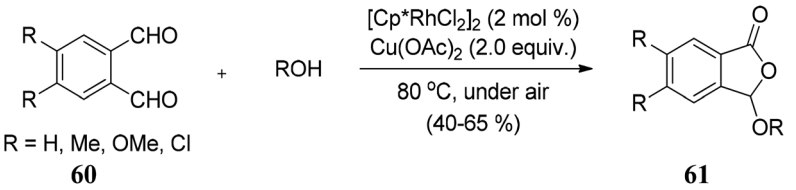
A variety of bifunctional phase-transfer catalysts (PTC) were examined to obtain 3-substituted phthalides in excellent enantioselectivity. Bifunctional PTC **75** (Fig. 5) gave the desired product in moderate ee's (51–71%).[73]

3.1.5 Oxa-Michael addition reaction to generate 3-substituted (±)-1(3*H*)-isobenzofuranones. Youn and co-workers[75] have developed NHC-catalyzed domino oxidation of 2-alkenylbenzaldehydes **81**, followed by oxa-Michael addition reaction to afford 3-substituted phthalides **83**. The protocol developed has a broad substrate scope and wide functional group tolerance. The success of the domino process could be achieved in two ways; by exploiting atmospheric oxygen as an oxygen atom source and by adding an electron-deficient olefin bearing hetero atom with lone pair of electrons. Also, molecular oxygen in air could play an essential role in transformation, as similar NHC-catalyzed reactions of the same substrates under inert atmosphere produce follow different reaction pathways (Scheme 11).

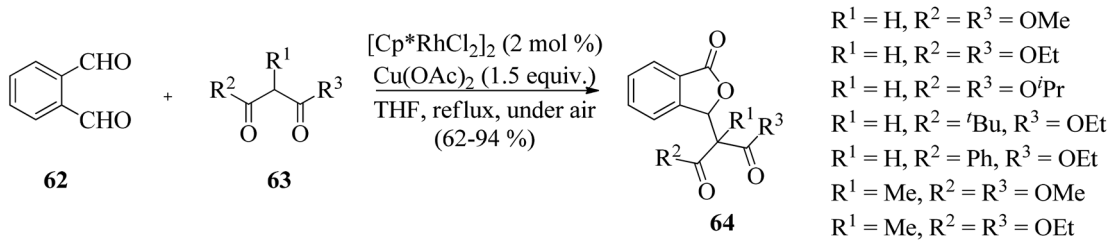
3.1.6 Friedel–Crafts alkylation reaction to generate 3-substituted (±)-1(3*H*)-isobenzofuranones. Tang and co-workers[76] have developed an efficient methodology to synthesize 3-indolyl-substituted phthalides **86** *via* Friedel–Crafts alkylation of indoles **85** with 3-hydroxy phthalide **84** using TsOH as the catalyst. The usefulness of the process was studied with variously substituted indoles which reacted efficiently at room temperature to afford phthalides in excellent yields (Scheme 12).



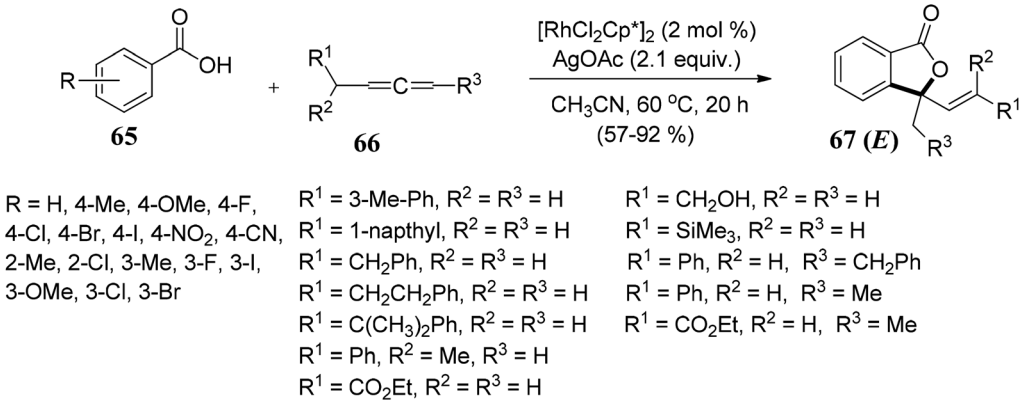
Scheme 3 Synthesis of 3-vinyl phthalides.



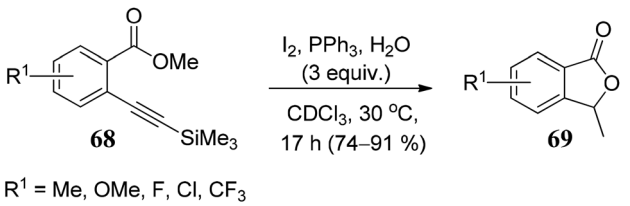
Scheme 4 Synthesis of 3-alkoxy phthalides.



Scheme 5 Synthesis of 3-alkyl phthalides.



Scheme 6 Scope of arenecarboxylic acids and allenes (synthesis of disubstituted phthalides).

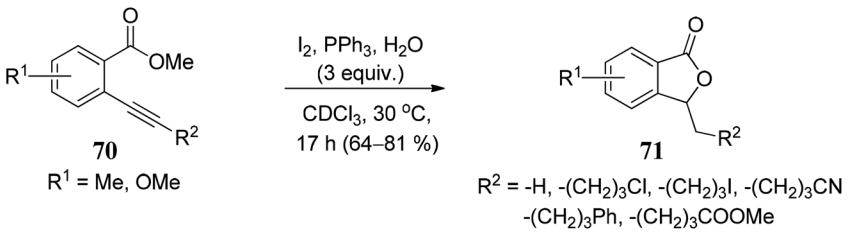


Scheme 7 Hydroiodination-triggered synthesis of 3-methylphthalides.

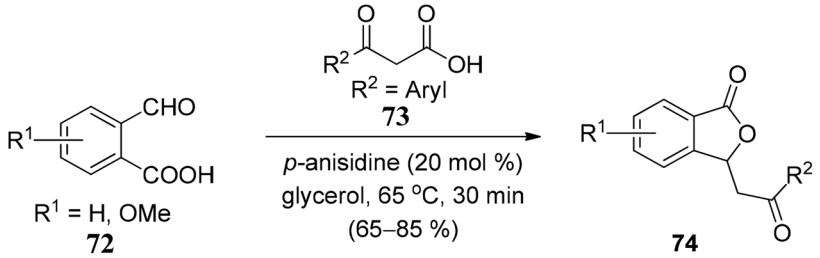
3.1.7 NBS mediated free-radical bromination to generate 3-substituted (±)-1(3*H*) isobenzofuranones. Li and co-workers[77] have devised a four-step strategy for the synthesis of 3-substituted phthalide. The condensation reaction of 3-ethoxyphthalide **89** with diethylmalonate carbanion followed by decarboxylation and hydrolysis gave 3-substituted phthalides **92** in 44% overall yield over four steps (Scheme 13). NBS mediated free-radical bromination of phthalide **87** gives **88**. The crude **88** was treated with hot ethanol, then cooled to give **89** as white solid.

3.1.8 Photochemical catalyzed synthesis of 3-substituted (±)-1(3*H*)-isobenzofuranones. Tatsugi and co-workers[78] demonstrated that the degassed alcoholic solution of indane-1,2,3-trione **93** could be photochemically irradiated to afford 3-alkoxycarbonylphthalides **94** as the major product. During the process, 3-alkoxyphthalide **95** was also obtained in minor quantities (Scheme 14).

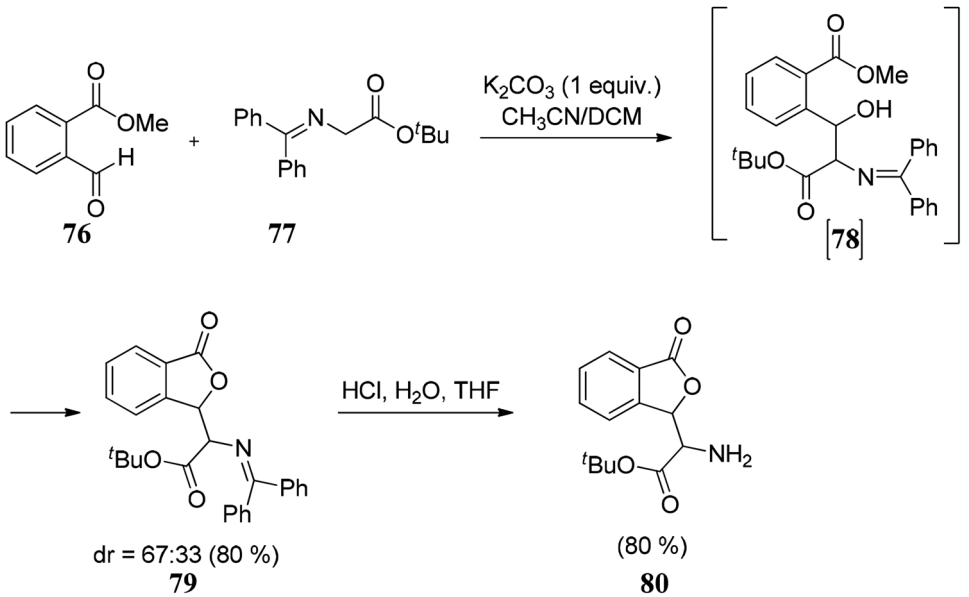
The initial step of the photochemical process could be the cleavage of a C–O bond to form semidione radical **93a**, which under rearrangement forms **93b**. Thus, **93b** can follow two pathways: (i) it can form the compound **93c**, which on reaction with ROH forms **93d** followed by protonation to give 3-alkoxycarbonylphthalides **94** or (ii) **93f** rearranges to **93g** followed by decarbonylation gave phthalides carbene which on quenching with ROH gave 3-alkoxyphthalide **95** (Scheme 15).



Scheme 8 Synthesis of 3-substituted phthalides triggered *via* hydroiodination.



Scheme 9 Synthesis of 3-substituted phthalides using β-keto acids as a nucleophile center.



Scheme 10 Synthesis of α-amino ester 3-substituted phthalide.

3.2 Recent methodologies to synthesize enantiomerically pure 3-substituted 1(3*H*)-isobenzofuranes

In this section, we have described recent approaches to synthesize enantiomerically pure 3-substituted 1(3*H*)-isobenzofuranes.

3.2.1 Synthesis of 3-substituted 1(3*H*)-isobenzofuranones using diverse organozinc reagents. Huang and co-workers[79] demonstrated a new protocol for the synthesis of chiral 3-substituted phthalides **99** by carrying out catalytic asymmetric 1,2-addition of methyl 2-formylbenzoates **98**, followed by lactonization, using diverse organozinc reagents (Scheme 16). They developed a chiral phosphoramide ligand–Zn(II) complex, which was synthesized from (1*R*,2*R*)-diphenylethyelendiamine **100** as catalyst. The efficiency of the process is highlighted by the fact that the enantiopure phthalide **99** was obtained in excellent yields (~95%) and good enantioselectivities (~89%).

Carlos and co-workers[80] carried out the asymmetric catalytic synthesis of 3-aryl phthalides **102** *via* sequential asymmetric arylation–lactonization pathway. In the presence of a chiral amino naphthol ligand, the reactive arylating agents, generated by boron–zinc exchange, were reacted with 2-formylbenzoates **101**, which was followed by lactonization to yield the corresponding chiral phthalides **102** in excellent yields and

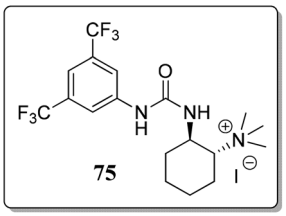


Fig. 5 Bifunctional phase-transfer catalyst.

enantioselectivities (~87–90% ee) (Scheme 17). The place of the substituent at the aryl ring was found to have a slight effect on the efficiency of the arylation reactions. The asymmetric addition of an aryl zinc reagent to the 2-formylbenzoate is the enantio determining step.

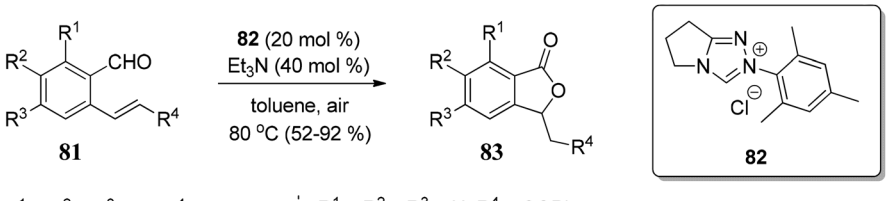
3.2.2 Synthesis of chiral 3-substituted phthalides *via* palladium-catalyzed Heck–Matsuda arylation of arenediazonium salt. Kattela and co-workers[81] have described an enantioselective synthesis of chiral 3-substituted phthalides *via* palladium-catalyzed Heck–Matsuda arylation of arenediazonium salt **104** with 2,3-dihydrofurans **105**, followed by $NaBH_4$ mediated reduction and lactonization pathway to give chiral phthalides **107** in overall yields and excellent enantioselectivities (up to 98% ee). The strategy was further extended for the synthesis of medicinally important chiral lactones, amines, and olefins (Scheme 18).

3.2.3 Novel derived metal complex ligand as a catalyst for the synthesis of chiral 3-substituted phthalides. Ge and co-workers[82] have developed the first asymmetric hydrogenation of 3-alkyl/arylidenephthalides **108** to furnish an extensive range of 3-substituted chiral phthalides **109** in admirable enantiomeric excesses (~98% ee). The hydrogenation process was catalyzed by a novel derived Ir^{I} complex of a spiro-[4,4]-1,6-nonadiene-based phosphine–oxazoline ligand (SpinPHOX) **110** as a catalyst. The effectiveness of the protocol further extended for the asymmetric synthesis of enantioselective drugs as well as the bioactive natural products (Scheme 19).

Zhang and co-workers[83] demonstrated a novel route for the reductive cyclization of 2-acylarylcarboxylate **111** *via* asymmetric transfer hydrogenation. The reaction was promoted by a new Ru(II)–diamine complex **113**, which catalyzes asymmetric transfer hydrogenation and *in situ* lactonization to provide enantiomerically pure 3-substituted phthalides **112** (Scheme 20).

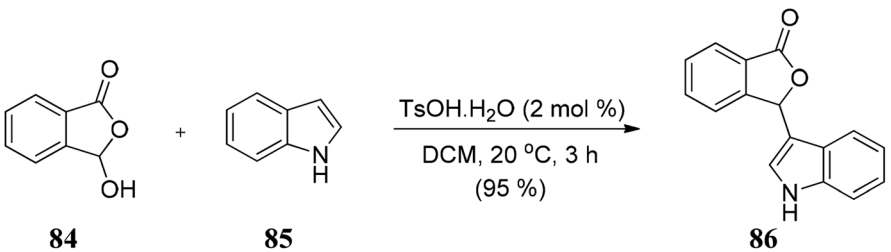
The observed excellent enantioselectivity can be explained by a preferable transition state of the Ru–TsDBuPEN complex and ethyl 2-acylarylcarboxylate substrates, which determines the chirality. Hydrogen bonding with the neighboring ester function group of the 2-acylarylcarboxylate substrate might also be accountable for the observed selectivity (Fig. 6).

Kumbhar and co-workers[84] synthesized bipyridyl ligands. These chiral ligands were applied in the synthesis of chiral phthalides. The reaction sequence involved chromium-catalyzed enantioselective Nozaki–Hiyama–Kishi allylation of

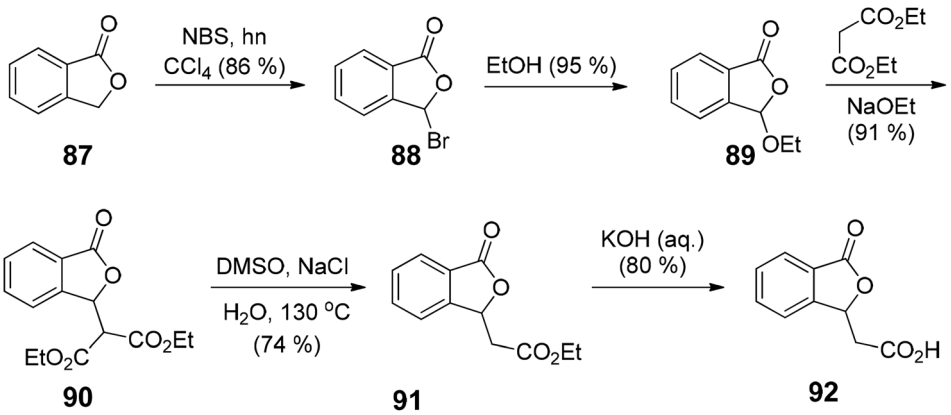


$R^1 = R^2 = R^3 = H$, $R^4 = CO_2Et$
$R^1 = R^2 = R^3 = H$, $R^4 = CO_2Me$
$R^1 = R^2 = R^3 = H$, $R^4 = CO_2{}^nBu$
$R^1 = R^2 = R^3 = H$, $R^4 = CO_2{}^tBu$
$R^1 = R^2 = R^3 = H$, $R^4 = CONMe_2$
$R^1 = R^2 = R^3 = H$, $R^4 = CN$
$R^1 = R^2 = R^3 = H$, $R^4 = COMe$
$R^1 = R^2 = R^3 = H$, $R^4 = COEt$
$R^1 = R^2 = R^3 = H$, $R^4 = COPh$
$R^1 = R^2 = R^3 = H$, $R^4 = PO(OEt)_2$
$R^1 = R^2 = H$, $R^3 = Me$, $R^4 = CO_2Et$
$R^1 = H$, $R^2 = OMe$, $R^3 = H$, $R^4 = CO_2Et$
$R^1 = H$, $R^2 = OMe$, $R^3 = H$, $R^4 = CO_2{}^tBu$
$R^1 = H$, $R^2 = OMe$, $R^3 = OMe$, $R^4 = CO_2Et$
$R^1 = OMe$, $R^2 = H$, $R^3 = H$, $R^4 = CO_2Me$
$R^1 = H$, $R^2 = Cl$, $R^3 = H$, $R^4 = CO_2Et$
$R^1 = H$, $R^2 = F$, $R^3 = H$, $R^4 = CO_2Et$

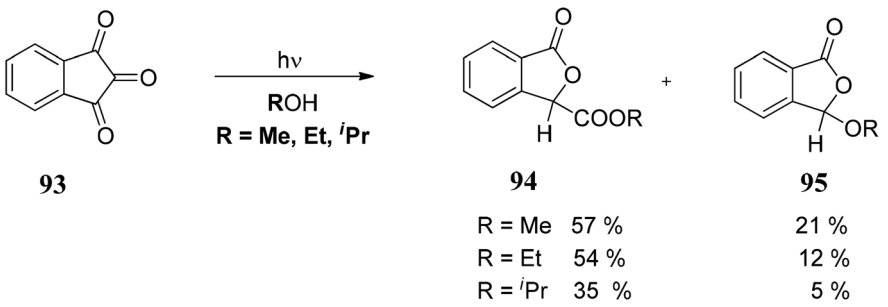
Scheme 11 NHC-catalyzed domino oxidation/oxa-Michael addition of 2-alkenylbenzaldehydes.



Scheme 12 Synthesis of 3-indolyl-substituted phthalides.



Scheme 13 Synthesis of 3-substituted phthalides.



Scheme 14 Photochemical reactions of indane-1,2,3-trione.

substituted benzaldehydes **114**, followed by lactonization gave enantiopure phthalides **116** with an optimal ee of 99%. Chiral Cr(II) complex developed using bipyridine alcohol and $CrCl_3$. This utility of the protocol was further extended by accomplishing the synthesis of (*S*)-cytosporone E in three steps (Scheme 21).

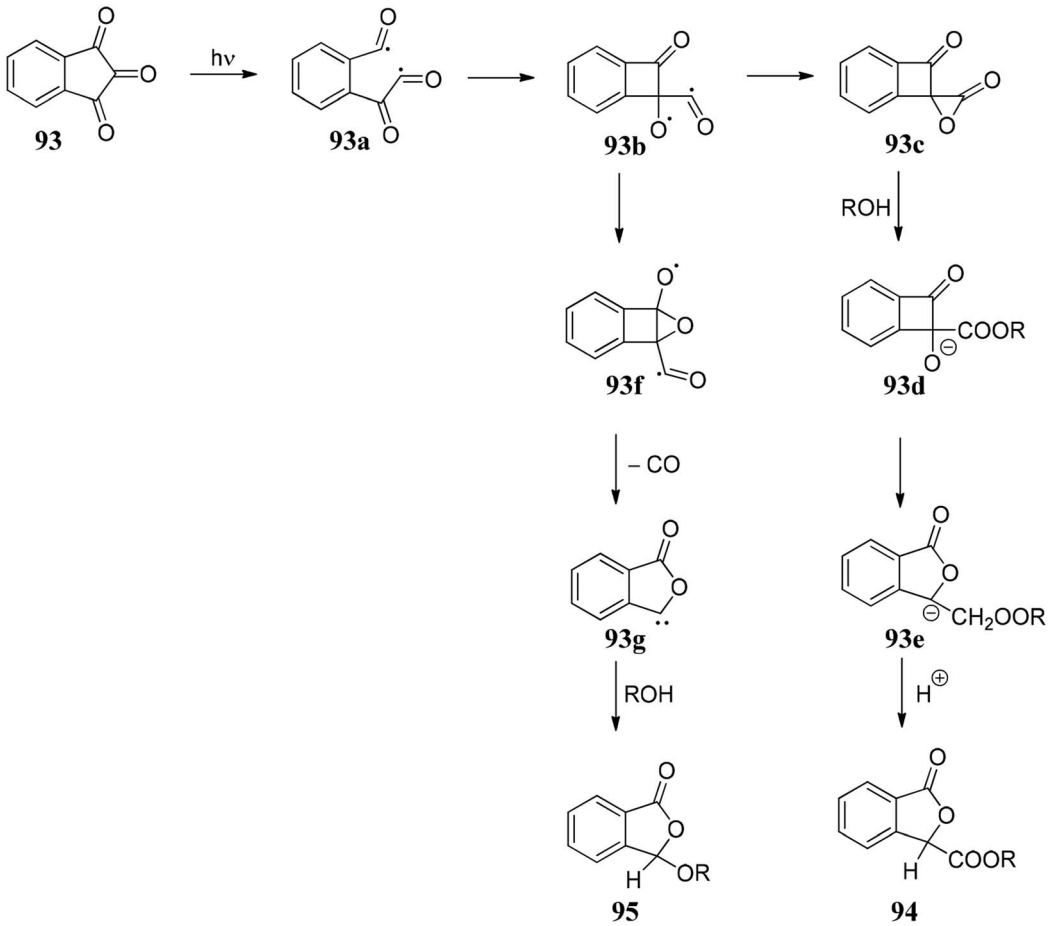
Lu and co-workers[85] established an extremely effective and enantioselective approach towards the synthesis of bioactive 3-substituted chiral phthalides **119**. The protocol involved ruthenium-catalyzed hydrogenation followed by lactonization of 2-acylarylcarboxylates **117** to furnish 3-substituted chiral phthalides. Different chiral phosphine ligands were employed to obtain good enantioselectivity, the best among them was (*S*)-SunPhos **118**, which helped in the induction of enantioselectivity >99% ee (Scheme 22).

3.2.4 Chiral bifunctional cinchonine as an organocatalyst for the synthesis of chiral 3-substituted phthalides. Youn and co-workers[86] developed an asymmetric domino oxidation/oxa-Michael addition reaction wherein an N-heterocyclic carbene (NHC) **121** and a chiral bifunctional cinchonine organocatalyst **122** work cooperativity to furnish the chiral 3-substituted phthalides **123**. The use of a bifunctional cinchonine catalyst helps in achieving excellent enantioselectivity, where it functions both as a base (quinuclidine) and hydrogen bond donor, thus activating nucleophile and electrophile, respectively. Cinchonine works both as a Brønsted base for the generation of NHC as well as a bifunctional catalyst for asymmetric induction (Scheme 23).

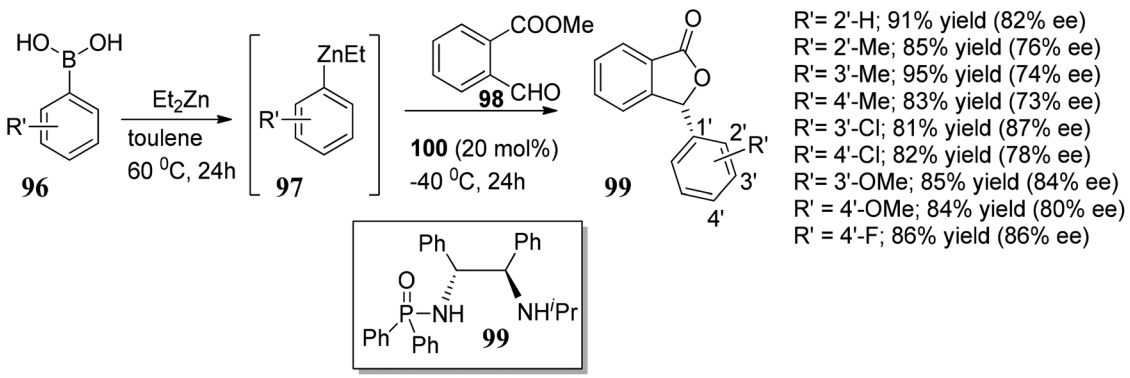
3.2.5 Synthesis of chiral 3-substituted phthalides *via* a nucleophilic addition reaction. Zhang and co-workers[87] described a two-step asymmetric route for 3-substituted phthalides **130**. The chiral amide **126** was subjected to the treatment with isopropyl magnesium chloride followed by reaction with various aldehydes **128** (Scheme 24). Intramolecular cyclization of the substrate allowed the synthesis of 3-substituted phthalides **130** (~88% ee).

Davis and co-workers[88] developed an enantioselective approach towards the synthesis of 3-substituted phthalides by the addition of phthalide anions **133** to chiral-sulfinimines (*N*-sulfinyl imines) **132**. The present approach was extended for the synthesis of chiral 3-substituted isoquinolones and 3-substituted 4-hydroxy isoquinolines, respectively (Scheme 25).

3.2.6 Tandem aldol-lactonization reactions for the synthesis of chiral 3-substituted phthalides. Ray and co-workers[89] carried out chiral Brønsted acid **140** catalyzed, tandem mannich–lactamization, and aldol-lactonization reactions to achieve the enantioselective synthesis of phthalides **143** in good to excellent enantioselectivities (Scheme 26). The developed protocol has broad substrate scope, and a variety of substituted aromatic aldehydes and aromatic amine were used.



Scheme 15 Proposed mechanistic pathway.



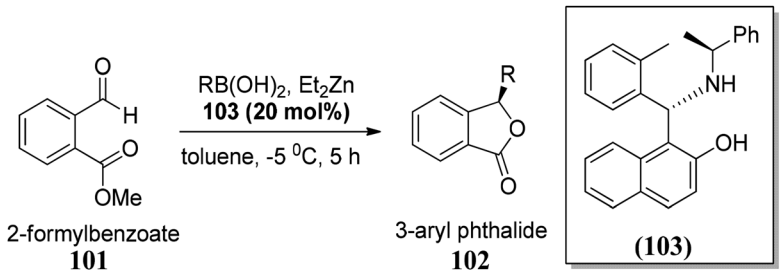
Scheme 16 Asymmetric 1,2-addition/lactonization tandem reaction of methyl 2-formylbenzoate.

4. Application of 3-substituted 1(3*H*)-isobenzofuranones for the construction of crucial molecular architecture

As discussed in Table 1, we can state that phthalide moiety is present in various biologically active natural products. In this section, we aim to provide some of the examples of 3-substituted 1(3*H*)-isobenzofuranones for the construction of important molecular architecture.

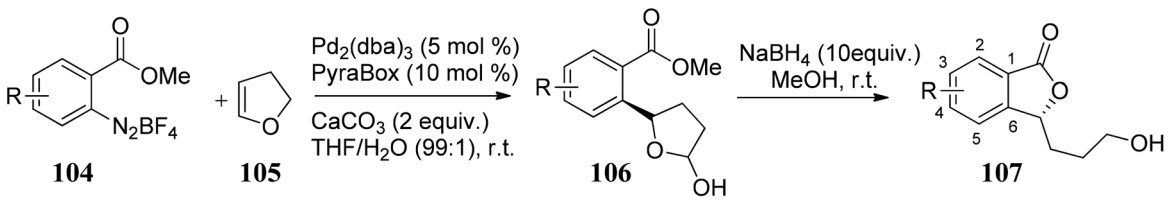
4.1 Annulation of stabilized phthalide anions with Michael acceptors

Annulation with stabilized phthalide anions along with Michael acceptors is a powerful and convenient tool for obtaining the quinoid natural products. Many natural products consist of a standard quinone unit. The exciting structures and vital



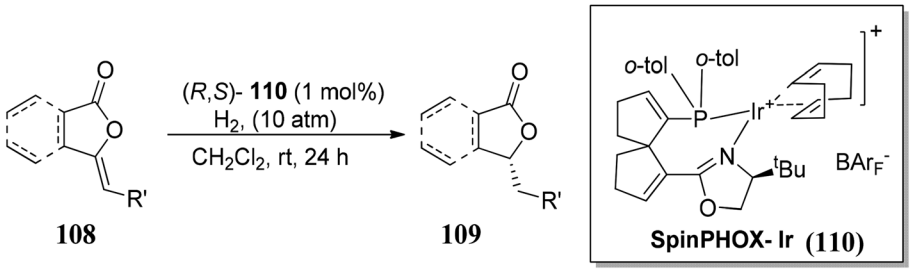
R = Ph, 80% yield (91% ee)
R = *o*-tolyl, 86% yield (83% ee)
R = *p*-tolyl, 90% yield (91% ee)
R = 4-PhC_6H_4, 71% yield (81% ee)
R = 4-ClC_6H_4, 58% yield (85% ee)
R = 4-BrC_6H_4, 95% yield (83% ee)
R = 4-$MeOC_6H_4$, 71% yield (91% ee)

Scheme 17 Asymmetric arylation–lactonization sequence.



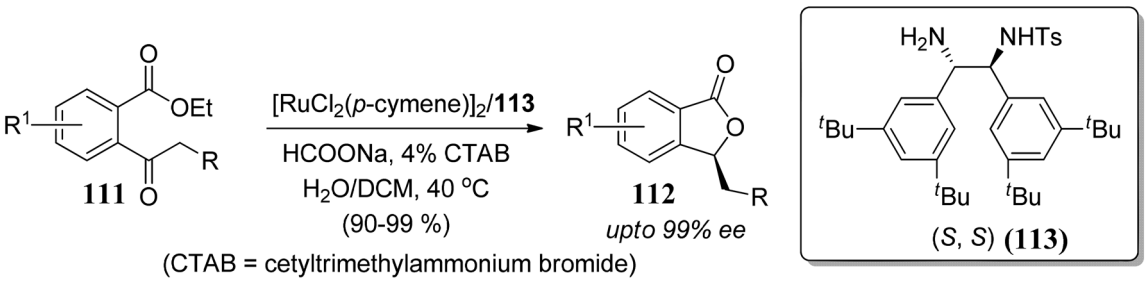
R = 2-Me; 66% yield (99% ee); R = 3-OMe; 62% yield (98% ee); R = 3-NO_2; 55% yield (98.5% ee);
R = 3-Cl; 60% yield (98.5% ee); R = 3-Br; 55% yield (98.5% ee); R = 3-Br & 4-^{i}Pr; 58% yield (98.5% ee);
R = 3-OMe & 4-OMe; 56% yield (98.5% ee); R = 2-OMe & 4-OMe; 58% yield (98.5% ee)

Scheme 18 Heck–Matsuda arylation of dihydrofurans.



R' = ^{n}Bu; 98% yield (95% ee)
R' = Me; 86% yield (86% ee)
R' = Et; 93% yield (96% ee)
R'= ^{n}Pr; 98% yield (95% ee)
R' = ^{n}Pentyl; 94% yield (91% ee)
R' = C_6H_5; 100% yield (97% ee)
R' = Napthalene; 98% yield (94% ee)
R' = Thiophene; 40% yield (95% ee)

Scheme 19 Asymmetric hydrogenation of the 3-alkyl/arylidenephthalides.



R = R^1 = H; 97% yield (98% ee)
R = Me, R^1 = H; 95% yield (98% ee)
R = $ClCH_2(CH_2)_2$, R^1 = H; 95% yield (99% ee)
R = Ph, R^1 = H; 96% yield (99% ee)
R = 4-ClC_6H_4, R^1 = H; 98% yield (99% ee)
R = 4-MeC_6H_4, R^1 = H; 93% yield (99% ee)
R = 4-$MeOC_6H_4$, R^1 = H; 96% yield (99% ee)
R = 4-$MeSC_6H_4$, R^1 = H; 99% yield (99% ee)
R = 4-$CF_3C_6H_4$, R^1 = H; 96% yield (99% ee)

R = 3,5-$(MeO)_2C_6H_3$, R^1 = H; 93% yield (99% ee
R = 2-thienyl, R^1 = H; 97% yield (99% ee)
R = 1-napthyl, R^1 = H; 98% yield (99% ee)
R = 4-quinolyl, R^1 = H; 94% yield (98% ee)
R = 4-Cl-phenoxyl, R^1 = H; 94% yield (99% ee)
R = 4-Cl-phenylthio, R^1 = H; 97% yield (98% ee)
R = Ph, R^1 = 4-Br; 90% yield (99% ee)
R = Ph, R^1 = 5-Br; 93% yield (99% ee)
R = Ph, R^1 = 4,5-Cl_2; 98% yield (98% ee)
R = Ph, R^1 = 4,5-C_6H_4; 97% yield (98% ee)

Scheme 20 Asymmetric synthesis of 3-substituted phthalides by ruthenium-catalyzed transfer hydrogenation.

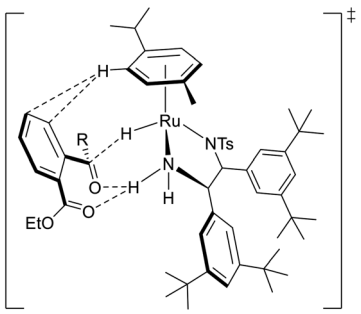


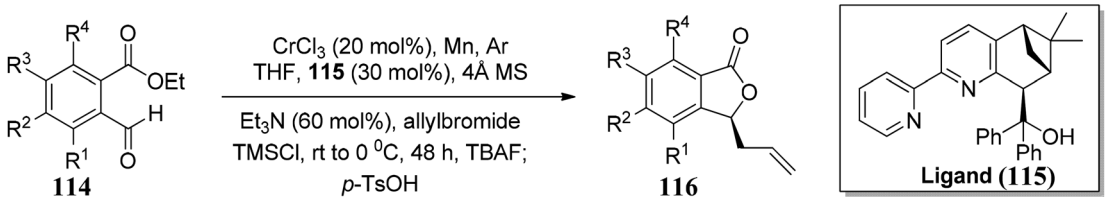
Fig. 6 Proposed transition state.

biological activities[90] of these natural products have provided an influential forum for organic chemists to explore this area of research. The general protocol for this reaction was discovered in the late 1970s simultaneously by Hauser[91] and Kraus.[92]

The phthalide annulation involves the deprotonation of a stabilized phthalides **144** by a strong base and *in situ* capture of anion by a suitable Michael acceptor **145** followed by Dieckmann-like condensation to afford a bicyclic compound **148** (Scheme 27). Compound **148** undergoes mild oxidation to form biphenol derivatives **149.** This methodology presents an elegant way to synthetic naphthol derivatives *via* phthalide chemistry.

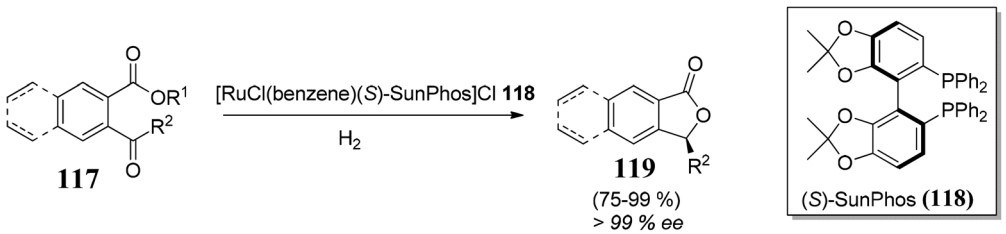
Chaturvedi and co-workers[93] developed a novel route to utilize unsaturated phosphonates for annulation reaction as Hauser acceptors. Good yields of phosphorylated 1,4-dihydroxynaphthalenes **153** are obtained, which on further oxidation results in their corresponding 1,4-naphthoquinones **154.** The reaction is successful in providing an efficient, straightforward, and powerful approach for synthesizing disubstituted naphthalene-1,4-diols **153.** Naphtha-1,4-diones **154** consist of a various (hetero) aryl groups positioned at 3 and a phosphonate group positioned at 2 (Scheme 28).

4.1.1 Metal-free catalytic annulation to develop enantioriched highly functionalized dihydronaphthoquinones. A metal-free catalytic annulation is developed by Zhuang and co-workers,[94] which involves Lewis base-mediated asymmetric allylic alkylation and a novel asymmetric intramolecular acyl cyanation of alkenes. This route provides a novel method to obtain enantioriched highly functionalized dihydronaphthoquinones **160** and chiral 3,3-disubstituted phthalides **158** having quaternary



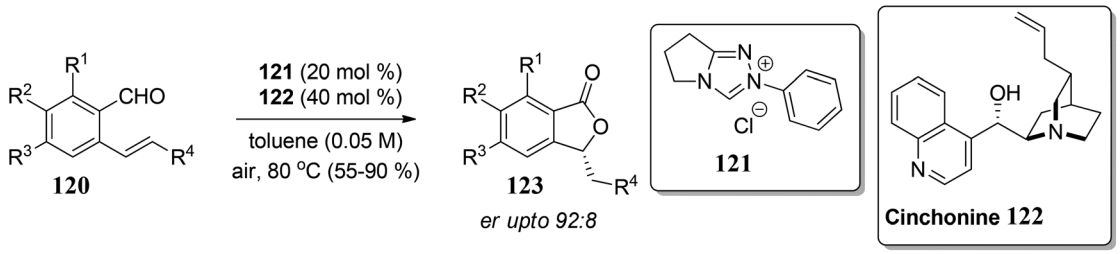
R^1= H, R^2= OCH_3, R^3= H, R^4 =OCH_3; 87% yield (97% ee)
R^1= H, R^2= OCH_3, R^3= OCH_3, R^4 =H; 85% yield (94% ee)
R^1= OCH_3, R^2= OCH_3, R^3= OCH_3, R^4 =H; 89% yield (99% ee)
R^1= H, R^2= H, R^3= H, R^4 =H; 86% yield (96% ee)
R^1= H, R^2= H, R^3= OCH_3, R^4 =H; 90% yield (97% ee)
R^1= H, R^2= H, R^3= $N(CH_3)_2$, R^4 =H; 70% yield (96% ee)
R^1= H, R^2= Br, R^3= $N(CH_3)_2$, R^4 =H; 90% yield (98% ee)

Scheme 21 Enantioselective Nozaki–Hiyama–Kishi allylation.



R^1 = Me, R^2 = Me; 95% yield (99.6% ee)
R^1 = Et, R^2 = Me; 98% yield (99.6% ee)
R^1 = ^{i}Pr, R^2 = Me; 98% yield (99.2% ee)
R^1 = H, R^2 = Me; 92% yield (99.4% ee)
R^1 = Me, R^2 = Et; 94% yield (99.6% ee)
R^1 = Me, R^2 = ^{n}Pr; 94% yield (99.2% ee)
R^1 = Me, R^2 = ^{n}Bu; 96% yield (99.4% ee)
R^1 = Me, R^2 = ^{t}Bu; 58% yield (99.6% ee)
R^1 = Me, R^2 = C_6H_5; 95% yield (98.2% ee)
R^1 = H, R^2 = C_6H_5; 95% yield (96.2% ee)
R^1 = Me, R^2 = o-$CH_3C_6H_4$; 75% yield (99.2% ee)
R^1 = Me, R^2 = p-$CH_3C_6H_4$; 87% yield (33.8% ee)
R^1 = Me, R^2 = o-$CF_3C_6H_4$; 98% yield (99.4% ee)
Methyl 2-acetyl-5-methylbenzoate; 98% yield (99.0% ee)
Methyl 2-acetyl-5-chlorolbenzoate; 98% yield (99.4% ee)
Methyl 3-acetyl-2-napthoate; 98% yield (99.4% ee)

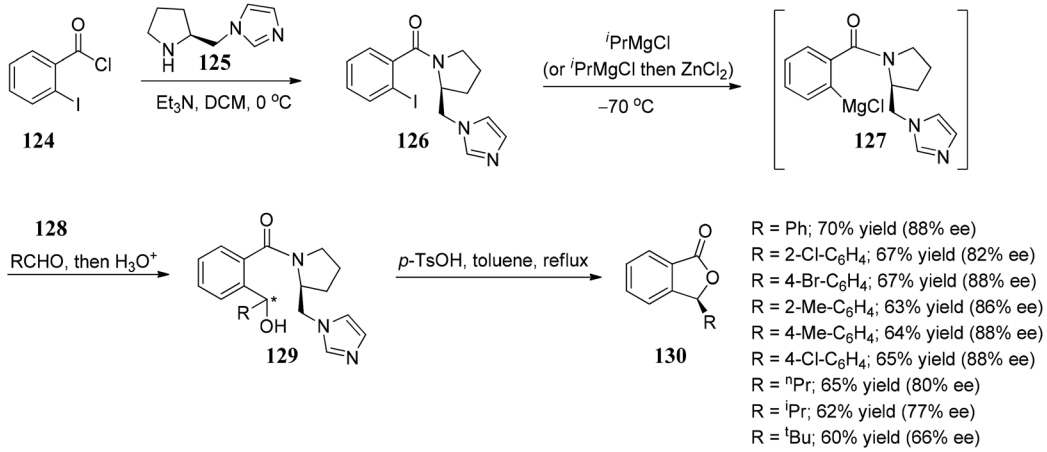
Scheme 22 Asymmetric hydrogenation of 2-acylarylcarboxylate.



$R^1 = R^2 = R^3 = H$, $R^4 = CO_2Et$; 72% yield (96% ee)
$R^1 = R^2 = R^3 = H$, $R^4 = CO_2Me$; 70% yield (95% ee)
$R^1 = R^2 = R^3 = H$, $R^4 = CO_2{}^nBu$; 71% yield (95.5% ee)
$R^1 = R^2 = R^3 = H$, $R^4 = CO_2{}^tBu$; 71% yield (96.5% ee)
$R^1 = R^2 = R^3 = H$, $R^4 = CN$; 55% yield (90.5% ee)
$R^1 = R^2 = R^3 = H$, $R^4 = COMe$; 72% yield (75.5% ee)

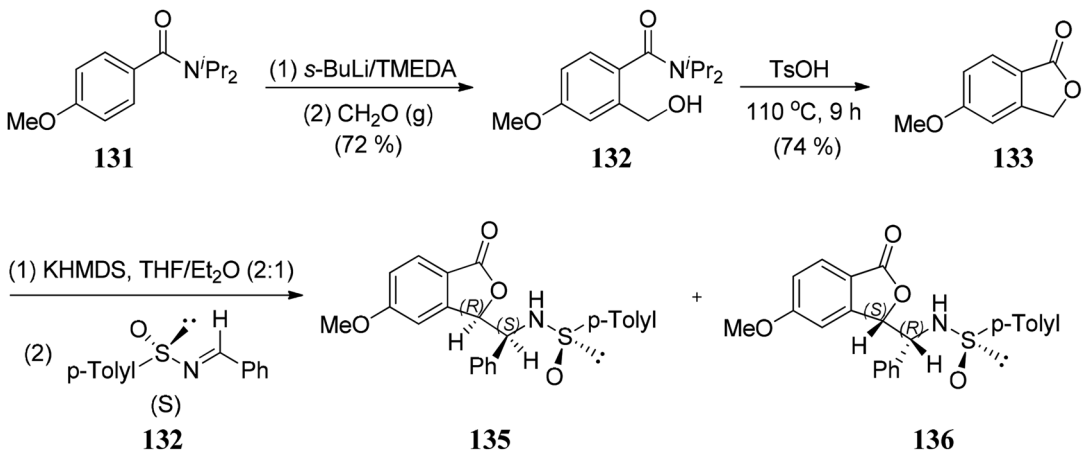
$R^1 = R^2 = R^3 = H$, $R^4 = PO(OEt)_2$; 90% yield (94% ee)
$R^1 = R^2 = H$, $R^3 = Me$, $R^4 = CO_2Et$; 75% yield (95.5% ee)
$R^1 = H$, $R^2 = OMe$, $R^3 = H$, $R^4 = CO_2{}^tBu$; 70% yield (95.5% ee)
$R^1 = H$, $R^2 = OMe$, $R^3 = OMe$, $R^4 = CO_2Et$; 63% yield (94.5% ee
$R^1 = OMe$, $R^2 = H$, $R^3 = OMe$, $R^4 = CO_2Me$; 74% yield (96% ee)

Scheme 23 Asymmetric oxidative cyclization of 2-alkenylbenzaldehydes.

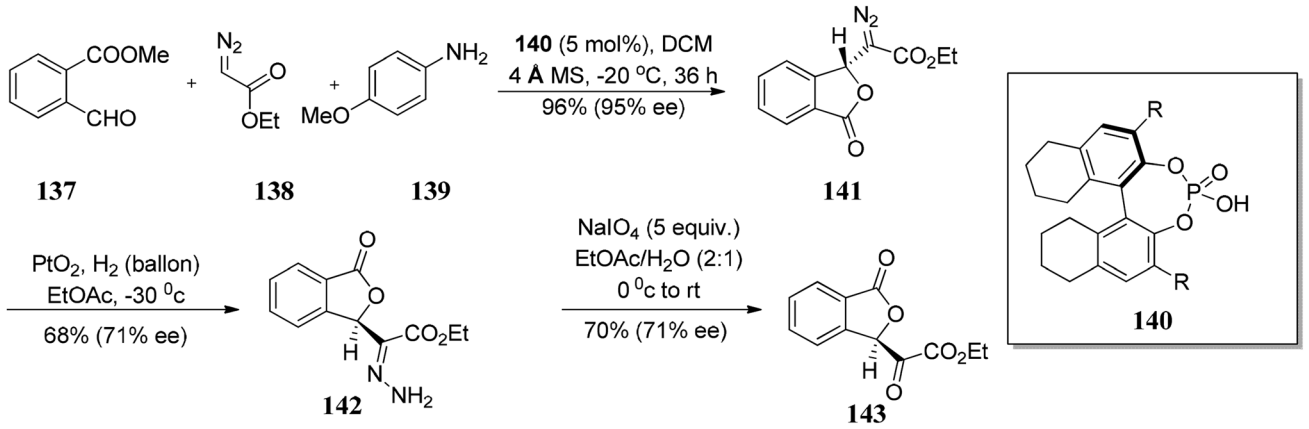


R = Ph; 70% yield (88% ee)
R = 2-Cl-C_6H_4; 67% yield (82% ee)
R = 4-Br-C_6H_4; 67% yield (88% ee)
R = 2-Me-C_6H_4; 63% yield (86% ee)
R = 4-Me-C_6H_4; 64% yield (88% ee)
R = 4-Cl-C_6H_4; 65% yield (88% ee)
R = ^{n}Pr; 65% yield (80% ee)
R = ^{i}Pr; 62% yield (77% ee)
R = ^{t}Bu; 60% yield (66% ee)

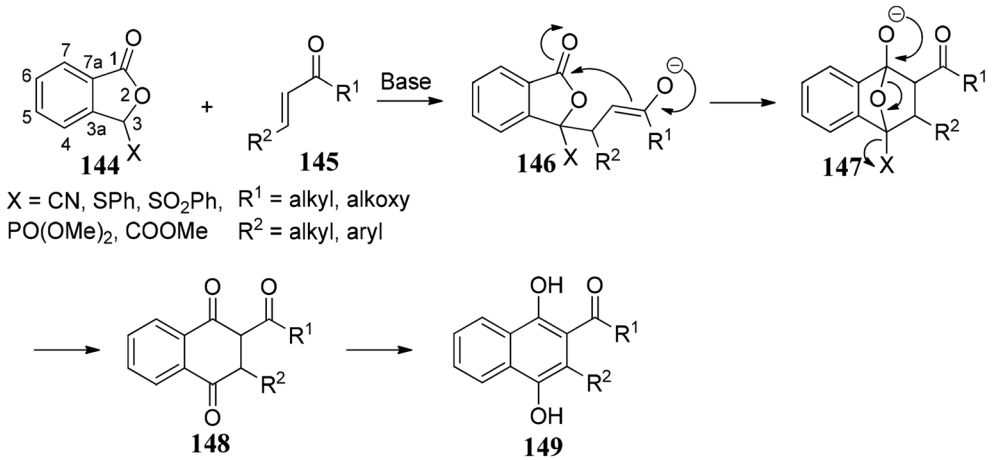
Scheme 24 Direct asymmetric synthesis of 3-substituted phthalides.



Scheme 25 Reaction of phthalide anion with enantiopure sulfinimines.



Scheme 26 Tandem aldol-lactonization reactions.



Scheme 27 Annulation of stabilized phthalide anions with Michael acceptors.

carbon centers (Schemes 29 and 30). The reaction involves the use of chiral bifunctional thiourea organocatalyst.

4.1.2 Hauser–Kraus annulation to give naphthoquinol–carbohydrate hybrids. Chakraborty and co-workers[95] described a regioselective approach to naphthoquinone/naphthoquinol–carbohydrate hybrids using 3-cyano phthalides **161** as one of the essential precursors. In this approach, anionic annulation of 3-cyano phthalides **161** takes place with an acrylate appended sugar moiety **162** (Scheme 31).

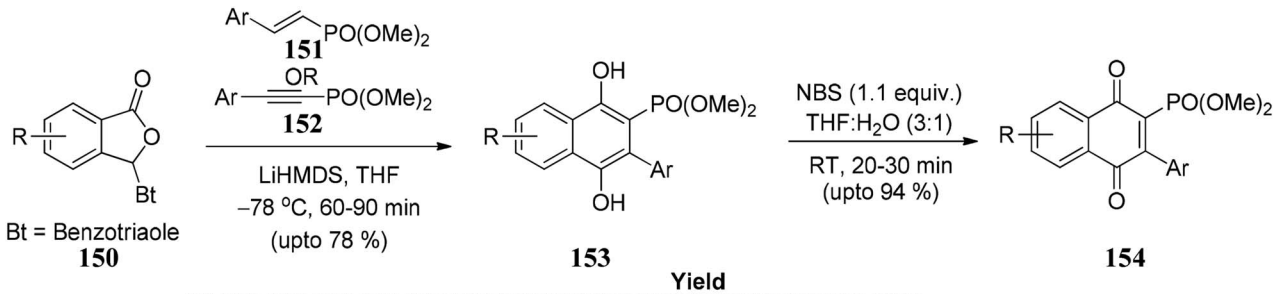
4.1.3 Total synthesis of uncialamycin *via* Hauser–Kraus annulation. Nicolaou and co-workers[96] described the total synthesis of uncialamycin, and a Hauser–Kraus annulation was employed as one of the critical reactions for the synthesis of uncialamycin core (Scheme 32).

4.1.4 Total synthesis of the griseusin B scaffold (bioactive natural product) *via* Hauser–Kraus annulation. Naysmith and co-workers[97] developed a convergent route for the synthesis of the griseusin B scaffold (bioactive natural product). The main steps of the synthetic journey include the highly effective one-pot Hauser–Kraus annulation followed by methylation and double deprotection–spirocyclization sequence that directly results in the target tetracyclic ring system (Scheme 33).

4.2 Total synthesis of (−)-α-noscapine

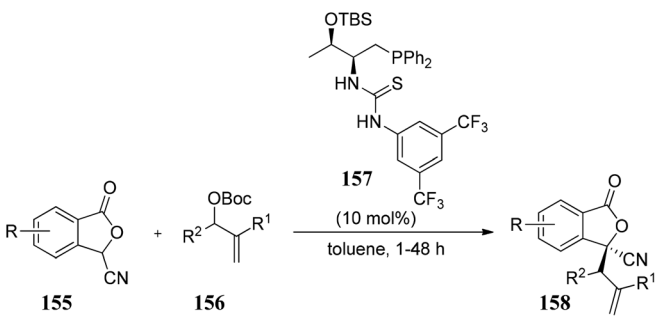
(−)-α-Noscapine (narcotine), which was initially isolated from *Papaver somniferum* L.,[98] is a non-addictive anti-tussive agent with little to no significant toxicity.[99] (−)-α-noscapine also displays other probable scientific utilities[100] for the treatment of life-threating diseases. Naturally occurring noscapine consists of two adjacent chiral centers: one at C-5′ position of tetrahydroisoquinoline ring and another at the C-3 position of phthalide framework.

Xu and co-workers[101] commenced with the synthesis of meconine-3-carboxylic acid **173**, which could be synthesized from pure 2,3-dimethoxybenzoic acid **171** and glyoxylic acid **172** in the presence of a conc. H_2SO_4. While the amine functionality **174** could be easily prepared from gallic acid over a nine-step sequence. The amide bond (C5′–C3 bond formation) was formed from the acyl chloride derivative of **173** and free amine **174** to give compound **175** in 89% yield (Scheme 34). The next step of the sequence was Bischler–Napieralski reaction in the



	Yield	
	Ar—PO(OMe)$_2$	Ar—≡—PO(OMe)$_2$
R = H, Ar = Ph	56 %	52 %
R = H, Ar = 4-NO_2-C_6H_4	78 %	75 %
R = H, Ar = 4-F-C_6H_4	68 %	58 %
R = H, Ar = 4-Br-C_6H_4	61 %	58 %
R = H, Ar = 4-Cl-C_6H_4	52 %	50 %
R = H, Ar = 3-F-C_6H_4	69 %	67 %
R = H, Ar = 3-Br-C_6H_4	67 %	67 %
R = H, Ar = 2-Br-C_6H_4	56 %	56 %
R = H, Ar = 3-OMe-C_6H_4	47 %	46 %
R = H, Ar = 1-napthyl	52 %	51 %
R = H, Ar = 2-thiophene	45 %	43 %
R = H, Ar = 4-F-C_6H_4	45 %	43 %
R = 6-Br, Ar = 4-Br-C_6H_4	42 %	39 %
R = 6-Br, Ar = 2-Br-C_6H_4	43 %	42 %
R = 7-Br, Ar = Ph	42 %	38 %
R = Ph, Ar = 4-F-C_6H_4	47 %	47 %
R = Ph, Ar = 3-Br-C_6H_4	41 %	39 %

Scheme 28 Hauser–Kraus annulation of 3-substituted phthalides.



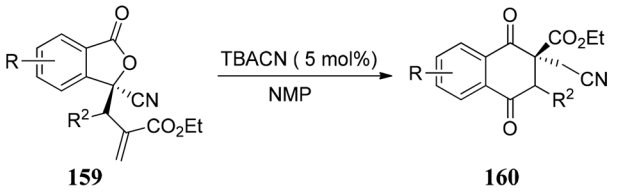
R = H, R^1 = Et, R^2 = H; 99% yield (92 % ee)
R = 4-Me, R^1 = Et, R^2 = H; 92% yield (88% ee)
R = 4-OMe, R^1 = Et, R^2 = H; 99% yield (89% ee)
R = 3-Me, R^1 = Et, R^2 = H; 92% yield (93% ee)
R = 2-OMe, R^1 = Et, R^2 = H; 91% yield (90% ee)
R = 3,4-Me, R^1 = Et, R^2 = H; 97% yield (95% ee)
R = 4,5-OMe, R^1 = Et, R^2 = H; 99% yield (92% ee)
R = 4-F, R^1 = Et, R^2 = H; 99% yield (96% ee)
R = 4-Cl, R^1 = Et, R^2 = H; 99% yield (96% ee)
R = 4-Br, R^1 = Et, R^2 = H; 99% yield (96% ee)
R = 3-F, R^1 = Et, R^2 = H; 99% yield (96% ee)
R = H, R^1 = Me, R^2 = H; 98% yield (90% ee)
R = H, R^1 = Butyl, R^2 = H; 97% yield (81% ee)

Scheme 29 Lewis base-catalyzed asymmetric allylic alkylation of 3-cyano phthalides.

presence of $POCl_3$. The cyclization took place efficiently to give imine, which was further reduced to afford tetrahydroisoquinoline **176**. After extensive optimization of $NaBH_4$/$NaBH_3CN$ mediated reduction, it was concluded that low reaction temperature was critical for the high diastereoselectivity and moderately high yields. Subsequently, Eschweiler–Clarke reaction was used to obtain an *N*-methylated compound, **177** in 75% yield. RANEY® Ni was used for hydrogenation of 177 to produce target compound **8**. Further recrystallization of the crude sample gave pure (±)-α-noscapine **8**.

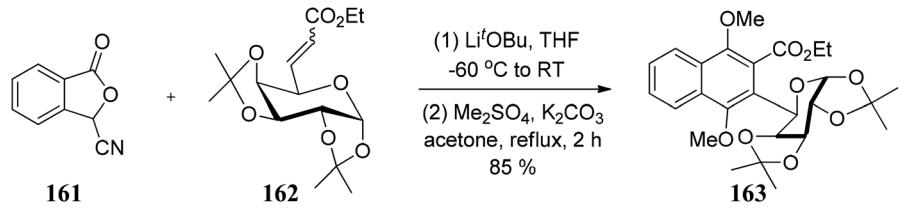
4.3 Total synthesis of olaparib

Olaparib is an FDA approved targeted therapy for the treatment of cancer. It is a PARP inhibitor, inhibiting poly ADP ribose polymerase (PARP), an enzyme that plays a role in DNA repair. It targets

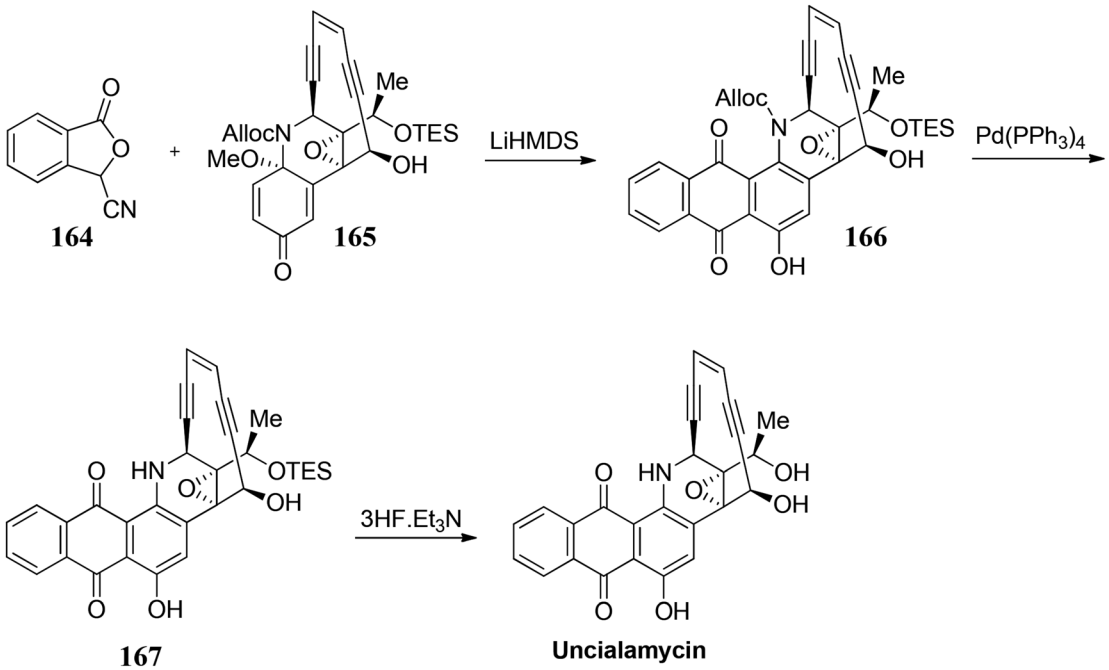


R = H, R^2 = H; 71% yield (95% ee)
R = 4-Me, R^2 = H; 67% yield (97% ee)
R = 4-OMe, R^2 = H; 55% yield (99% ee)
R = 3-Me, R^2 = H; 52% yield (86% ee)
R = 3,4-Me, R^2 = H; 64% yield (95% ee)
R = 4,5-OMe, R^2 = H; 55% yield (59% ee)
R = 2-OMe, R^2 = H; 52% yield (52% ee)
R = 4-F, R^2 = H; 48% yield (95% ee)
R = 4-Cl, R^2 = H; 47% yield (86% ee)
R = 4-Br, R^2 = H; 48% yield (83% ee)
R = 3-F, R^2 = H; 48% yield (83% ee)

Scheme 30 Annulation reaction of 3-substituted phthalides.



Scheme 31 Hauser–Kraus annulation to give naphthoquinol–carbohydrate hybrids.



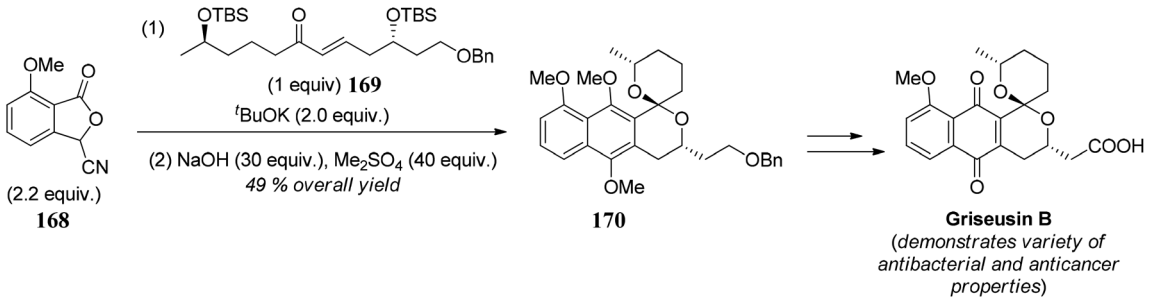
Scheme 32 Total synthesis of uncialamycin.

cancer cells in people with hereditary BRCA1 or BRCA2 mutations, which include some ovarian, breast, and prostate cancers.[102]

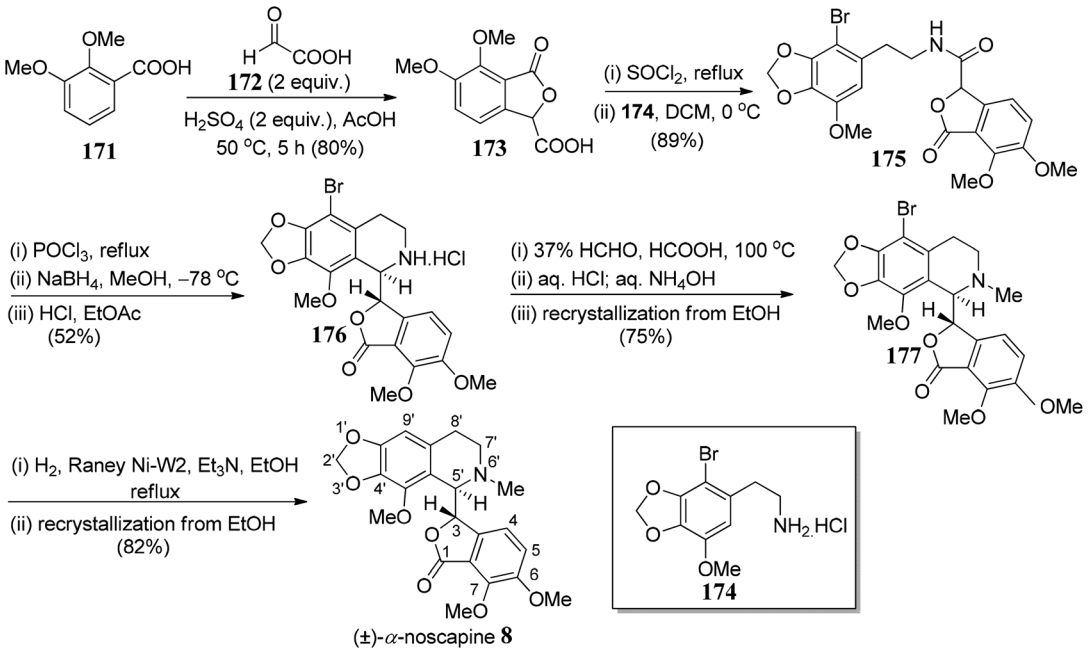
Lou and co-workers[103] demonstrated an effective protocol for the synthesis of olaparib. The synthesis initiated by 3-phosphonophthalide **178**, which on further reaction with aromatic aldehyde **179** gave **180**, which further on reaction with hydrazine hydrate underwent ring expansion to give **181**. **181** on amide coupling with **182** gave the desired drug, olaparib (Scheme 35).

4.4 Synthesis of cytogenin (a bioactive natural product)

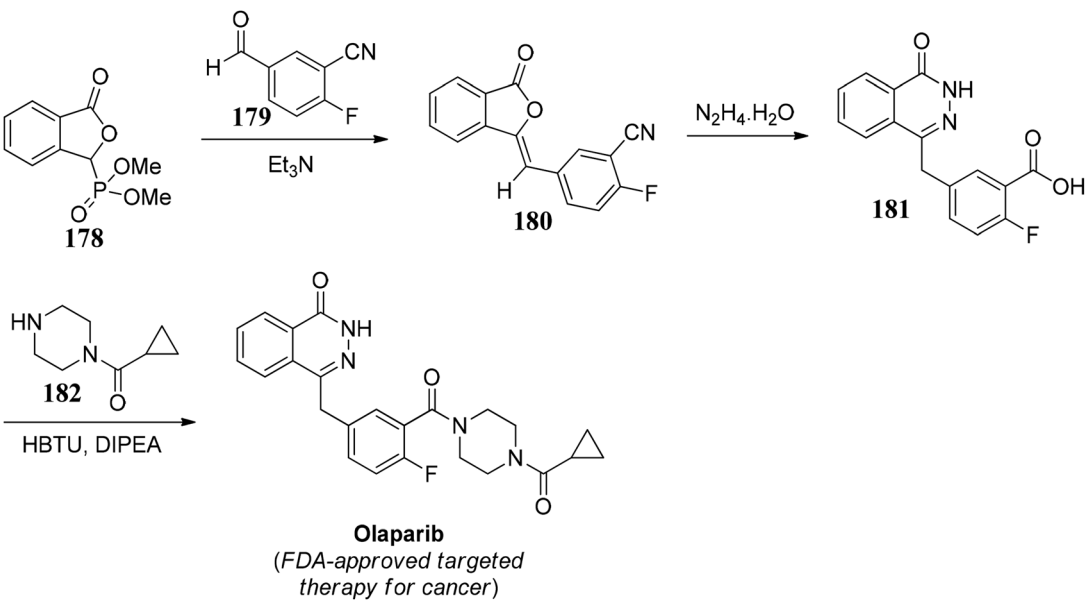
Gadakh[104] and co-workers developed a route for the synthesis of 3-carbethoxy-isocoumarins **184.** The reagent system used in this



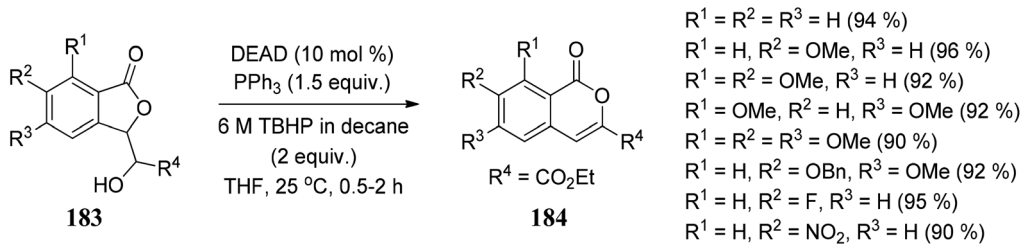
Scheme 33 Total synthesis of the griseusin B scaffold.



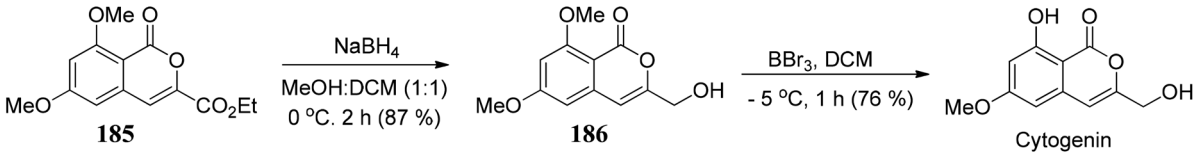
Scheme 34 Total synthesis of (±)-α-noscapine.



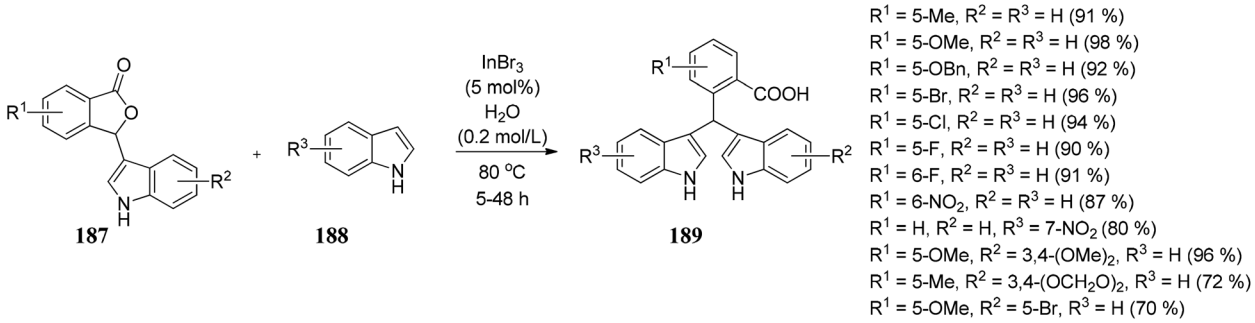
Scheme 35 Synthesis of FDA approved the anti-cancer drug olaparib.



Scheme 36 Intramolecular ring expansion of 3-substituted phthalides to isocoumarins.



Scheme 37 Synthesis of cytogenin'.



Scheme 38 $InBr_3$ catalyzed Friedel–Crafts reaction between indole and 3-indolyl-substituted phthalides.

methodology is DEAD/PPh_3/TBHP through 1,2-shift intramolecular ring expansion, or we can say that the simple elimination is dependent on the various functional groups present on 3-substituted phthalides (Scheme 36).

The methodology is also used to synthesize cytogenin (a bioactive natural product) (Scheme 37).

4.5 $InBr_3$-catalyzed Friedel–Crafts reaction on 3-indolyl-substituted phthalides to develop unsymmetrical bis(indolyl) methanes (BIMs)

Lin and co-workers[105] developed a convenient, efficient, and novel synthetic route for synthesizing the unsymmetrical bis(indolyl)methanes (BIMs) **189** *via* $InBr_3$-catalyzed Friedel–Crafts reaction by reacting indoles **188** with 3-indolyl-substituted phthalides **187** in water to obtain **189** in excellent yields (Scheme 38). These BIMs compounds present have excellent anti-Alzheimer's disease activity.

5. Conclusions

In the past decade, there has been considerable attention in the area of phthalides (more specifically 3-substituted phthalides) due to the development of various phthalides-based drugs. This has led to the development of elegant research methodologies with diverse applications in academic and industrial laboratories on micro- and macroscale operations. In light of the continued research in the area of 3-substituted phthalides, we have made an effort to present a critical review on the chemistry of 3-substituted phthalides. The chemistry of phthalides has been reviewed, but an independent and detailed review on the chemistry of 3-substituted phthalides is unavailable.

We have reviewed the isolation and biological activities of various 3-substituted phthalides. We have presented pivotal research methodologies for the synthesis of racemic and chiral 3-substituted phthalides. These newer approaches are essential for the development of newer and elegant strategies for the synthesis of phthalide-based or similar molecular architecture with broader substrate scope and higher stereoselectivities. Also, we have reviewed the application of 3-substituted phthalides as a precursor for the synthesis of natural products and their analogs. Through this review, we have provided enough contextual information on the chemistry of 3-substituted phthalides, which can inspire organic chemists to develop methodologies for the synthesis of biologically and medicinally important molecules.

Conflicts of interest

The authors declare no conflict of interest.

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