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Medicinal chemistry perspective on the structure–activity relationship of stilbene derivatives†

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Stilbenes are a small family of polyphenolic secondary metabolites produced in a variety of closely related plant species. These compounds function as phytoalexins, aiding plant defense against phytopathogens and plants' adaptation to abiotic environmental factors. Structurally, some important phenolic compounds have a 14-carbon skeleton and usually have two isomeric forms, *Z* and *E*. Stilbenes contain two benzene rings linked by a molecule of ethanol or ethylene. Some derivatives of natural (poly)phenolic stilbenes such as resveratrol, pterostilbene, and combretastatin A-4 have shown various biological activities, such as anti-microbial, anti-cancer, and anti-inflammatory properties as well as protection against heart disease, Alzheimer's disease, and diabetes. Among stilbenes, resveratrol is certainly the most popular and extensively studied for its health properties. In recent years, an increasing number of stilbene compounds have been investigated for their bioactivity. This review focuses on the assessment of synthetic stilbene derivatives in terms of their biological activities and structure–activity relationship. The goal of this study is to consider the structural changes and different substitutions on phenyl rings that can improve the desired medicinal effects of stilbene-based compounds beyond the usual standards and subsequently discover biological activities by identifying effective alternatives of the evaluated compounds.

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1. Introduction

Stilbene, 1,2-diphenylethylene, gets its name from the Greek word “stilbos”, which means “shining”.¹ It is a small molecule with a molecular weight of 180 g mol^{−1}.² The chemical structure of stilbene is composed of a 14-carbon skeleton. Stilbenes widely exist in nature and may act as phytoalexins, and some plants in response to pathogen attack and other stresses produce stilbenes as defense compounds.^{3,4} Stilbenes are abundant in plants with diverse vital biological activities.⁵ They are versatile structures composed of two aromatic rings linked by an ethylene moiety and exist in two diastereoisomeric forms, *E*/*Z*-isomers; thus, they can undergo *E*/*Z* isomerization, altering their general configuration and decreasing their biological activity.⁶ Stilbenes show different biological activities such as

anti-microbial, anti-oxidant, anti-leukemia, anti-platelet, protein tyrosine kinase inhibitor, anti-inflammatory, anti-cancer, and anti-HIV activities.⁷ Thus, stilbenes and their derivatives, which are vital groups of synthetic compounds and natural products, have attracted significant attention for their various pharmacological activities, complicated structures, and useful health properties.⁸ In addition to studying the various biological activities of stilbene analogues, the possible application of stilbene analogues as preservatives can be a new research direction.⁹ Moreover, these derivatives have attracted significant attention in diverse fields, including food biotechnology, drug discovery and development, and healthcare.¹⁰ The structure of stilbenes is not only limited to pharmaceutical and biological sciences but has also attracted attention from scientists because of their other vital properties, such as large geometrical alteration upon isomerization, high thermal stability of the *Z* isomer, high quantum yield for photochemical isomerization, and direct synthesis.^{11,12} Over the past years, increasing articles on stilbene have been found in the literature. Thus, it is a privileged structural scaffold belong to an enormous family of bioactive molecules, including synthetic molecules and natural products.^{11,13} More than 400 stilbene derivatives have been identified, which include different structures with various substituents at diverse positions.¹⁴ Hydroxylated stilbenes, such as resveratrol, pterostilbene, pinosylvin, and combretastatin A-4 (CA-4), are natural compounds that exhibit many biological activities (Fig. 1).¹² Resveratrol and its

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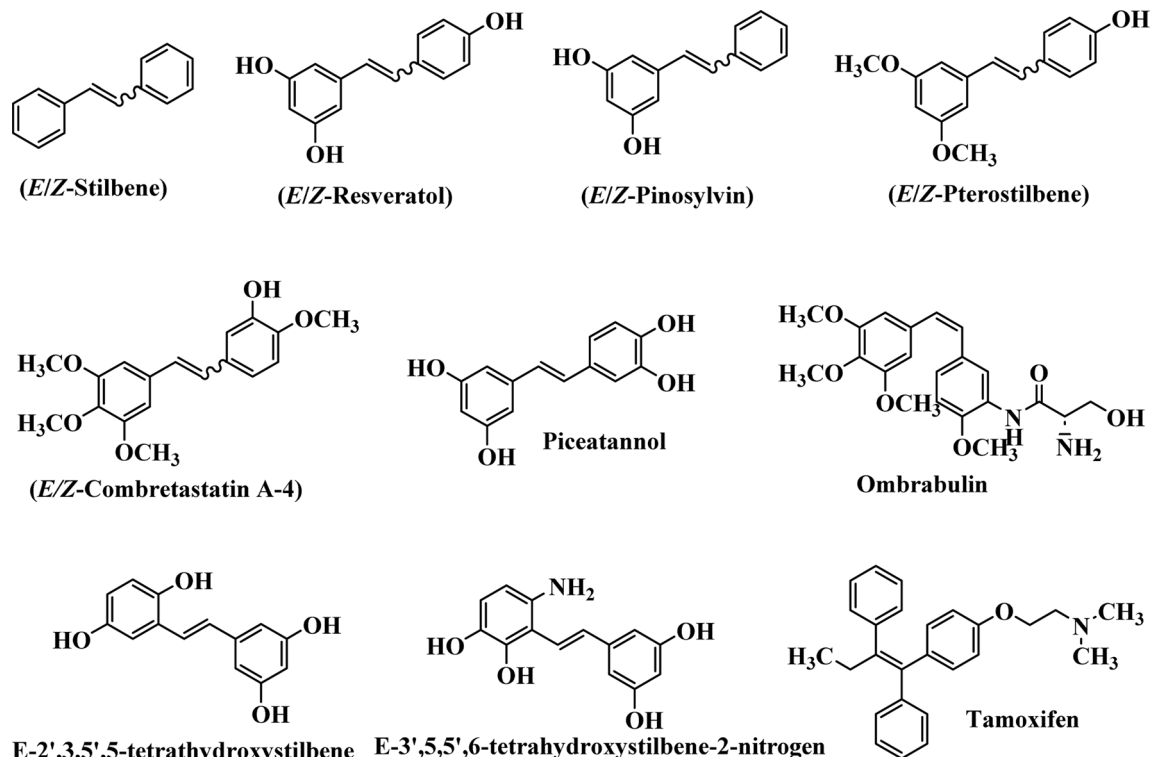


Fig. 1 Some chemical structures of well-known stilbene-based derivatives and drugs.

analogues are well-known for their antioxidant properties against reactive oxygen species (ROS), which cause oxidative damage to biological substances and play a role in aging and inflammation.¹⁵ Resveratrol, a naturally occurring phytoalexin found in grapes and other plants, has been shown to inhibit carcinogenesis and tumor cell cycle progression, as well as interfere with intracellular signal transduction regulating cell survival and apoptosis (programmed cell death) in various human cancer cell lines.^{16,17} Piceatannol (PIC) (*E*-2',3',4',5-tetrahydroxystilbene) is a phenolic compound (stilbenoid) and a hydroxylated analogue of resveratrol (Fig. 1). Grapes, passion fruit, white tea, Japanese knotweed, Asian legume, and Korean rhubarb are some crucial sources of PIC. However, because the level of PIC in grapes is lower than that of resveratrol, it has received significantly less research attention compared to resveratrol. Scientists have reported that the seeds of passion fruit (*Passiflora edulis*) have a high content of PIC, which displays various biological activities such as protection of the skin from ultraviolet B irradiation, inhibition of melanogenesis, promotion of collagen synthesis, a vasorelaxant effect and Sirt1 induction activity. PIC possesses potent antioxidant activity and has chemopreventive and anti-cancer properties.¹⁸ Z-CA-4 is a polyphenol, which was first isolated from an African bush willow tree in 1982, *Combretum caffrum*. It is recognized for its potent anti-angiogenic and anti-tumor activities and potent depolymerizing agents as well as a strong tubulin polymerization inhibitor.^{13,19} Numerous derivatives have been developed to search for compounds with higher biological activity, such as ombrabulin, which shows higher activity than CA-4 (Fig. 1).

Currently, it is being studied in phase III clinical trials for the treatment of advanced-stage soft-tissue carcinoma.²⁰ In January 2013, Sanofi said it discontinued the development of ombrabulin after disappointing results from phase III clinical trials. Furthermore, phosphate derivatives have demonstrated good activity and have been used in clinical trials.²¹ Interestingly, in 2006, Li *et al.*³ synthesized stilbene derivatives with substituted hydroxyl groups and found that two of these compounds, *E*-2',3,5',5-tetrahydroxystilbene and *E*-3',5,5',6-tetrahydroxystilbene-2-nitrogen, inhibited SARS coronavirus replication using an *in vitro* model (Fig. 1). Thus, stilbene-based compounds can also be considered as promising anti-COVID-19 drug candidates due to their ability to disrupt the spike protein.⁶ Tamoxifen, a stilbene derivative, is currently used to treat several types of breast cancer in women, as well as a hormone treatment for male breast cancer (Fig. 1).²⁰ Recently, many scientific institutions have been conducting research on stilbenes as alternative antibiotic growth stimulants. These compounds can be produced in plants by combining coumaric acid and cinnamic acid. Chalcones and flavanols can also be used for their synthesis. They have fungistatic properties (they inhibit fungi growth), toxic properties to fungi (they kill fungi), and estrogenic properties.²² Stilbenes may decrease obesity by regulating fat metabolism pathways such as adipogenesis, lipogenesis, lipolysis, and thermogenesis. Researchers are also investigating stilbene derivatives for cell proliferation and cytochrome P450 inhibitory activity.^{23,24} Natural product research, combined with the powerful possibilities provided by synthetic chemistry may provide an excellent method for



discovering new structures and identifying therapeutic targets.¹³

Other stilbene-based drugs that have been approved for use include dienestrol, toremifene, clomifene, tapinarof, raloxifene, ospemifene, and hydroxystilbamidine. Furthermore, some derivatives are under continuing clinical trials, such as cystic fibrosis-NCT04166396, chronic obstructive pulmonary disease-NCT03819517, chemoprevention-NCT04266353, combretastatin A1 di-phosphate/CA-1P, also known as OXI-4503 (acute myelogenous leukaemia and myelodysplastic syndromes-NCT02576301), pterostilbene or benvitimod, fispemifene, afimoxifene, droloxifene, and enclomiphene.¹¹ Moreover, Ramizol, a first-generation stilbene-based antibiotic, is effective against 100 clinical isolates of *C. difficile*,²⁵ and presently is under pre-clinical testing for the treatment of *C. difficile*-related diseases.²⁶ Fosbretabulin (CA-4 phosphate) has been investigated in numerous clinical trials as monotherapy and combined therapy with other chemotherapeutic agents, such as carboplatin, paclitaxel, bevacizumab and pazopanib.²⁷

However, despite all these recognized biological activities and advantages, the poor solubility of these analogues presents a critical problem in terms of their bioavailability, and thus prevents stilbene analogues from exhibiting the required activity. Some studies have reported that the complexation of polyphenols with cyclodextrins (CDs) and micellar systems results in a noticeable improvement in their aqueous solubility, and even increases their stability and bioactivity.¹⁰ CDs were shown to be more helpful for improving the solubility of stilbene with the benefit of being less toxic to humans.²⁴ In addition, nanoformulation techniques have been newly applied to enhance the bioavailability and targeting ability of stilbene analogues.²⁸ Some researchers conjugated stilbene analogues

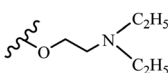
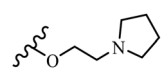
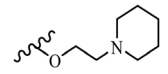
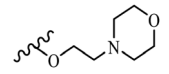
with mannose, glucose, and galactose to increase their solubility²⁹ or yield phosphate and carbamate prodrug salts.³⁰ Another strategy to increase their solubility is added or switching their groups with more polar groups based on their SAR.^{31–34}

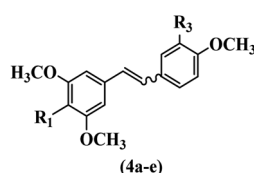
This study provides an overview of the synthetic compounds derived from the stilbene scaffold as anti-microbial, anti-cancer, antioxidant, liver enzyme inhibitors, anti-Alzheimer's, anti-diabetes, and other agents. These compounds have undergone chemical modifications, such as the addition of substituents with varying electronic effects or the incorporation of heteroaromatic groups instead of phenyl rings. The biological activity of these compounds is mainly influenced by their chemical structure and the substituent groups attached to them.³⁵ This comprehensive review mainly focuses on synthetic stilbene derivatives and the structure–activity relationship (SAR) studies on their various biological activities.

2. Anti-microbial activity

Pathogenic microorganisms have been a threat to humans throughout history, causing significant morbidity and mortality. Until the discovery of the first true antibiotic, penicillin, in 1928 and sulfa drugs in the 1930s, the only means of combating infectious diseases were various types of plant extracts, although their use yielded varying results.³⁶ Stilbenes have long been recognized as potent anti-bacterial agents, and they continue to pique the interest of many research groups working with various bacteria. The discovery of antibiotic activity against bacteria and fungi sparked interest in stilbene derivative research.^{3,4} One example is resveratrol, which naturally exists in plants and has anti-microbial activity against both

Table 1 Anti-microbial activity of *E/Z*-CA-4 derivatives

| Compound | <i>Z/E</i> | R_1 | R_3 | MIC ($\mu\text{g}/\text{disk}$) | | | | | |
|----------|------------|------------------|---|-----------------------------------|-----------------------|------------------|------------------|--------------------|----------------------|
| | | | | <i>C. albicans</i> | <i>N. gonorrhoeae</i> | <i>M. luteus</i> | <i>S. aureus</i> | <i>E. faecalis</i> | <i>C. neoformans</i> |
| 4a | <i>E</i> | OH | OH | 50–100 | 12.5–25 | — | — | — | 6.25–12.5 |
| 4b | <i>Z</i> | OCH ₃ |  | — | 50–100 | <6.25 | 25–50 | 50–100 | — |
| 4c | <i>Z</i> | OCH ₃ |  | — | — | 12.5–25 | 50–100 | — | — |
| 4d | <i>Z</i> | OCH ₃ |  | — | — | — | — | — | — |
| 4e | <i>Z</i> | OCH ₃ |  | — | 50–100 | — | — | — | — |



Gram-positive and Gram-negative bacteria.³⁷ Anti-microbial activity of stilbene derivatives is dependent on the presence of a hydroxyl group in their primary phenyl ring (2-hydroxy, 3-hydroxy, and 4-hydroxy derivatives). If the primary phenyl ring lacks a hydroxyl substituent, 2,5-dihydroxy substituents in the secondary phenyl ring are required for anti-microbial activity. The effect of hydroxyl groups on anti-microbial activity is not surprising, given that phenol is one of the most important anti-microbial agents.³⁸ The anti-microbial activity increases in derivatives with substituents (F, I, and Br). This can be explained by the change in the partition coefficient and increased permeability of cell membranes to fluoride derivatives, rather than the presence of the substituents themselves.^{39,40}

Pettit *et al.*⁴¹ described the synthesis and assessment of the anti-microbial activity of *E/Z*-CA-4 analogues. Most analogues were inactive against all strains. Among the synthesized compounds, *Z*-**4b** exhibited the highest anti-microbial activity against *M. luteus*. Also, *E*-**4a** having OH groups in the 4- and 3'-positions on its phenyl ring showed activity against *C. neoformans*; however, none of the compounds showed activity against this strain. Also, the *N,N*-diethylamino moiety in compound **4b** in the 3'-position on the phenyl ring was replaced with *N*-pyrrolidinyl in **4c**, which showed less activity against *S. aureus*, *E. faecalis*, and *M. luteus*. In addition, the presence of hydrophilic groups improved the anti-microbial activity compared to lipophilic groups (**4d** and **4e**) against *N. gonorrhoeae*. The results showed that the anti-bacterial activity was greater than anti-fungal activity. According to the obtained results, the *Z*-isomers showed stronger anti-microbial activity than the *E*-isomers (Table 1).

Wyrzykiewicz *et al.*⁴² synthesized *E*-piperidino and morpholino stilbenes and assessed their anti-microbial activity. Among the analogues, **8a** showed an anti-microbial effect against all the tested strains (*S. aureus*, *S. faecalis*, *B. subtilis*, *E. coli*, *C. albicans*, and *A. fumigatus*). Among the compounds, **8b** and **8c** exhibited the highest activity against *S. faecalis* and *B. subtilis* (aerobic). These compounds showed almost similar activity as chloramphenicol against these two strains. Also, the presence of an NO₂ group in the 4'-position on the phenyl ring in **8d** compared to **8e** (unsubstituted) displayed higher activity against *S. aureus*, *S. faecalis*, *B. subtilis*, and *A. fumigatus*. It seems that the presence of an electron-withdrawing group (EWG) such as NO₂ in the 4'-position on the phenyl ring plays a vital role in anti-microbial activity. In addition, increasing or decreasing the linker length had no significant effect (*e.g.*, **8a** and **8f**) against *S. faecalis* and *B. subtilis*. Compounds **8a-f** were only endowed with weak anti-microbial activity against *S. aureus* and *A. fumigatus* compared to chloramphenicol and amphotericin B. Most of the screened compounds showed moderate to weak anti-fungal activity (*C. albicans* and *A. fumigatus*). All the tested compounds displayed an insignificant effect against *K. pneumoniae* and *P. aeruginosa*. According to the results, Gram-positive bacteria are more susceptible to the target compounds than Gram-negative bacteria due to the absence of an outer membrane (Table 2).

Chanawanno *et al.*⁴³ synthesized pyridinium and quinolinium stilbene benzenesulfonate hybrids and evaluated their anti-bacterial activity. The quinolinium derivatives showed better activity compared to pyridinium derivatives. In the first series, quinolinium derivatives **12a-j** exhibited higher activity against Gram-positive than Gram-negative bacteria. Derivatives

Table 2 Chemical structures of *E*-piperidino and morpholino stilbenes

| Compound | <i>n</i> | R ₁ | R | MIC (μg mL ⁻¹) | | | | | |
|-----------------|----------|-----------------|---|----------------------------|--------------------|--------------------|----------------|--------------------|---------------------|
| | | | | <i>S. aureus</i> | <i>S. faecalis</i> | <i>B. subtilis</i> | <i>E. coli</i> | <i>C. albicans</i> | <i>A. fumigatus</i> |
| 8a | 2 | H | | 10 | 100 | 100 | 100 | 50 | 50 |
| 8b | 2 | H | | 7.5 | 7.5 | 5 | — | 50 | 50 |
| 8c | 5 | NO ₂ | | 10 | 7.5 | 10 | — | — | 50 |
| 8d | 4 | NO ₂ | | 10 | 100 | 10 | — | 100 | 10 |
| 8e | 4 | H | | — | — | — | — | 50 | 50 |
| 8f | 4 | H | | 5 | 100 | 100 | — | — | 100 |
| Chloramphenicol | — | — | — | 5 | 5 | 5 | 5 | — | — |
| Amphotericin B | — | — | — | — | — | — | — | 10 | 1 |

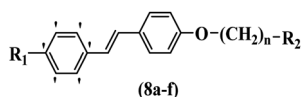


Table 3 Chemical structures of pyridinium and quinolinium stilbene benzenesulfonate derivatives

(12a-j, 15a-j)

| Compound | Ar | R ₁ | R ₂ | MIC (μg mL ⁻¹) | | | | | |
|----------|----|----------------------------------|------------------|----------------------------|--------------------|--------------------|----------------------|-----------------|------------------|
| | | | | <i>S. aureus</i> | <i>B. subtilis</i> | <i>E. faecalis</i> | <i>P. aeruginosa</i> | <i>S. typhi</i> | <i>S. sonnei</i> |
| 12a | | N(CH ₃) ₂ | Br | 2.34 | 2.34 | 2.34 | 300 | 300 | 2.34 |
| 12b | | N(CH ₃) ₂ | Cl | 2.34 | 2.34 | 2.34 | 300 | 300 | 2.34 |
| 12c | | N(CH ₃) ₂ | CH ₃ | 2.34 | 2.34 | 2.34 | 300 | 300 | 2.34 |
| 12d | | N(CH ₃) ₂ | OCH ₃ | — | 75 | 2.34 | 300 | 300 | 2.34 |
| 12e | | OC ₂ H ₅ | CH ₃ | — | 9.37 | 37.5 | — | — | 150 |
| 12f | | OC ₂ H ₅ | Br | 300 | 18.75 | 37.5 | — | — | 75 |
| 12g | | OC ₂ H ₅ | OCH ₃ | — | 18.75 | 75 | — | — | 150 |
| 12h | | OC ₂ H ₅ | Cl | — | 75 | 75 | — | — | 300 |
| 12i | | OC ₂ H ₅ | NH ₂ | 37.5 | 37.5 | 37.5 | — | — | 75 |
| 12j | | N(CH ₃) ₂ | NH ₂ | 75 | 18.75 | 75 | 150 | 75 | 75 |
| 15a | | N(CH ₃) ₂ | OCH ₃ | 150 | 150 | 150 | 150 | 150 | 150 |
| 15b | | OC ₂ H ₅ | OCH ₃ | 150 | — | — | — | — | — |
| 15c | | OC ₂ H ₅ | NH ₂ | — | — | — | — | — | — |
| 15d | | N(CH ₃) ₂ | Cl | — | 300 | — | 300 | 300 | — |
| 15e | | N(CH ₃) ₂ | NH ₂ | — | — | — | — | — | — |



Table 3 (Contd.)

(12a-j, 15a-j)

| Compound | Ar | R ₁ | R ₂ | MIC (μg mL ⁻¹) | | | | | |
|-----------------------|----|----------------------------------|-----------------|----------------------------|--------------------|--------------------|----------------------|-----------------|------------------|
| | | | | <i>S. aureus</i> | <i>B. subtilis</i> | <i>E. faecalis</i> | <i>P. aeruginosa</i> | <i>S. typhi</i> | <i>S. sonnei</i> |
| 15f | | N(CH ₃) ₂ | CH ₃ | 300 | 150 | 300 | 150 | 300 | 300 |
| 15g | | OC ₂ H ₅ | CH ₃ | — | 300 | 150 | 37.5 | 150 | 150 |
| 15h | | OC ₂ H ₅ | Br | — | — | — | — | 300 | 300 |
| 15i | | OC ₂ H ₅ | Cl | — | — | — | — | — | — |
| 15j | | N(CH ₃) ₂ | Br | — | — | — | — | — | — |
| Benzalkonium chloride | — | — | — | <2.34 | 150 | 9.37 | 300 | 9.37 | — |
| Vancomycin | — | — | — | 9.37 | 2.34 | 9.375 | 2.34 | 2.34 | 2.34 |

12a–c were the most potent compounds against all the tested Gram-positive bacteria. These compounds showed higher activity than that of the benzalkonium chloride drug and vancomycin. All quinolinium analogues were ineffective against *P. aeruginosa* and *S. typhi*. Also, the presence of EWG in the 4-position of the benzenesulfonate moiety resulted in higher antibacterial activity toward an electron-donating group (EDG) (e.g., **12a** vs. **12d**) against *S. aureus* and *B. subtilis*. Likewise, replacing OC₂H₅ in **12e** with a (CH₃)₂NH group in **12c** in the 4-position on the benzenesulfonate moiety increased the activity against all the strains. The presence of a substitution in the 4-position on the benzenesulfonate moiety increased the activity of the quinolinium derivatives by 2–4 times (**12a–j**). However, substitution in the 4-position of the benzenesulfonate moiety did not significantly improve the anti-bacterial activity of quinolinium derivatives (e.g., **12f**) against *S. aureus* and *B. subtilis*. Compounds **12a–j** were ineffective against all the tested Gram-negative bacteria. In the second series, the compounds containing a (CH₃)₂NH group in the 4'-position on the phenyl ring exhibited better activity than that containing an OC₂H₅ group in the same position (**15a** vs. **15b**). All the pyridinium derivatives (**15a–j**) showed less potency than benzalkonium chloride and vancomycin. According to the results, both hydrophilic and lipophilic groups had a similar effect on anti-bacterial activity (Table 3).

He *et al.*⁴⁴ synthesized stilbene derivatives containing a 1,3,4-oxadiazole moiety and evaluated their fungicidal activity. Compound **19a** inhibited cucumber *P. cubensis* with significant inhibitory activity comparable to fungicides. Most of the compounds exhibited moderate to weak control efficacy against *S. cucurbitacearum* (e.g., **19b**). Also, changing the position of the NO₂ group on the phenyl ring in 2'-position in **19c** to the 3'- and 4'-positions in **19d** and **19e** enhanced the activity against *P. cubensis* and *C. lagenarium*, respectively. Moreover, among the halogenated compounds, the EWG and small size of F showed the highest activity (**19f**). The shifting of the nitrogen atom from the 2'- to 3'-position of the pyridine ring in compounds **19g** and **19h** increased the activity against *P. cubensis* and decreased the activity against *C. lagenarium* and *S. cucurbitacearum*, respectively. In addition, the presence of an anthracene ring in **19i** showed lower activity than **19j** with a naphthalene ring against *P. cubensis* and *C. lagenarium*. Also, the compounds containing EWG demonstrated better anti-fungal activity compared to that containing EDG (**19k** vs. **19l**) against *P. cubensis* and *C. lagenarium*. The results showed that hydrophilic groups were more potent than lipophilic groups (**19c** vs. **19m**). Also, the presence of substitution on the phenyl ring reduced the activity (e.g., **19n** and **19b**). In addition, the presence of an extra substitution on the phenyl ring decreased the activity (e.g., **19k** and **19o**) (Table 4).



Table 4 Chemical structures of stilbene derivatives containing a 1,3,4-oxadiazole moiety

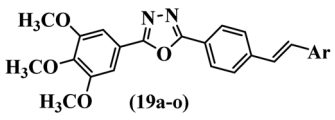
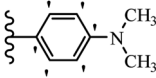
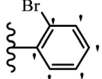
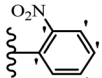
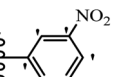
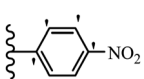
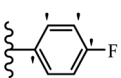
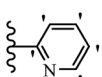
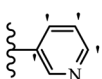
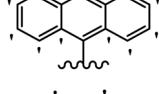
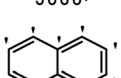
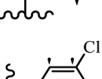
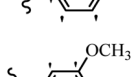
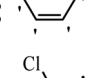
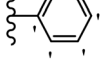
| Compound | Ar | Control efficacy (%) | | |
|----------|---|----------------------|----------------------|---------------------------|
| | | <i>P. cubensis</i> | <i>C. lagenarium</i> | <i>S. cucurbitacearum</i> |
| |  | | | |
| 19a |  | 71.38 | 30.26 | 44.84 |
| 19b |  | 8.37 | 26.38 | 69.34 |
| 19c |  | 48.34 | 56.07 | 35.36 |
| 19d |  | 50.13 | 83.82 | 46.83 |
| 19e |  | 63.42 | 66.72 | 32.23 |
| 19f |  | 52.20 | 65.14 | 72.05 |
| 19g |  | 18.38 | 52.88 | 45.14 |
| 19h |  | 42.67 | 37.58 | 40.27 |
| 19i |  | 15.3 | 14.29 | 53.09 |
| 19j |  | 36.01 | 37.98 | 51.18 |
| 19k |  | 65.01 | 82.43 | 32.03 |
| 19l |  | 44.13 | 37.90 | 47.62 |
| 19m |  | 32.66 | 31.48 | -9.348 |
| 19n |  | 58.77 | 50.03 | 55.178 |



Table 4 (Contd.)

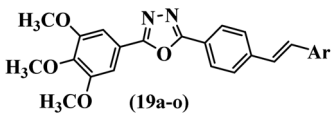
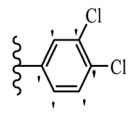
| Compound | Ar | Control efficacy (%) | | |
|---|---|----------------------|----------------------|---------------------------|
| | | <i>P. cubensis</i> | <i>C. lagenarium</i> | <i>S. cucurbitacearum</i> |
|  (19a-o) | | | | |
| 19o |  | -4.08 | 44.81 | 8.03 |
| Fungicides | — | 70.13 | 81.57 | 69.02 |

Table 5 Synthetic compounds of fluorine-containing stilbene

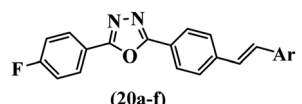
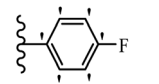
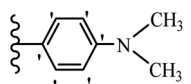
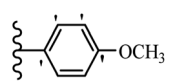
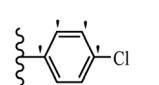
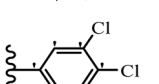
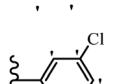
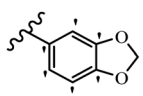
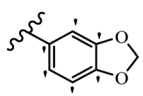
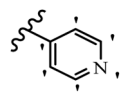
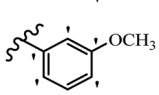
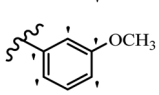
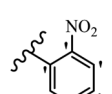
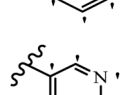
| Compounds | Ar | Control efficacy (%) | |
|---|---|----------------------|--------------------|
| | | <i>C. lagenarium</i> | <i>P. cubensis</i> |
|  (20a-f) | | | |
| 20a |  | 83.4 | 54.6 |
| 20b |  | 38.1 | 70.2 |
| 20c |  | 61.3 | 66.0 |
| 20d |  | 54.1 | 53.5 |
| 20e |  | 60.8 | 34.8 |
| 20f |  | 64.3 | 52.4 |
| Fungicides | — | 82.7 | 72.5 |

Table 6 Chemical analogues of oxadiazole–stilbene hybrids

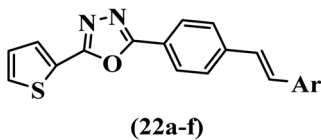
| Compounds | Ar | EC ₅₀ (μg mL ⁻¹) |
|-------------|---|---|
| 21a |  | 144.6 |
| 21b |  | 231.3 |
| 21c |  | >400 |
| 21d |  | 345.9 |
| 21e |  | 382.9 |
| 21f |  | >400 |
| 21g |  | >400 |
| Resveratrol | — | 315.6 |

Jian *et al.*⁴⁵ synthesized fluorine-containing stilbene derivatives and assessed their anti-fungal activity. The synthesis method was the same as that in a previous study.⁴⁴ Compounds **20a** and **20b** exhibited relatively high fungicidal potency against *C. lagenarium* and *P. cubensis* and were comparable to fungicides against both strains. Moreover, EDG showed higher activity than EWG (**20c** vs. **20d**) against *C. lagenarium* and *P.*

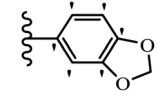
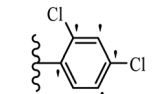
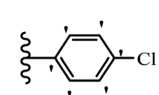
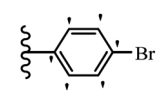
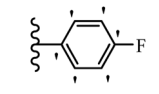
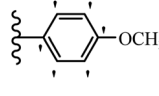
cubensis. In addition, compound **20e** with two Cl atoms in the 3'- and 4'-positions on the phenyl ring showed lower activity compared to **20f** having one Cl atom in the 3'-position against



Table 7 1,3,4-Oxadiazole–thiophene-based stilbene derivatives



(22a-f)

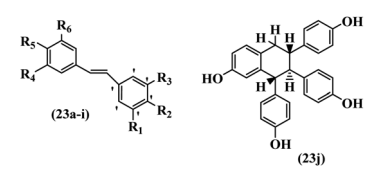
| Compounds | Ar | EC ₅₀ (μg mL ⁻¹) | |
|-------------|---|---|----------------------|
| | | <i>B. cinerea</i> | <i>C. lagenarium</i> |
| 22a |  | 155.4 | 248.2 |
| 22b |  | 172.1 | 261.7 |
| 22c |  | 187.7 | 279.6 |
| 22d |  | 175.5 | 263.7 |
| 22e |  | 180.1 | 268.9 |
| 22f |  | 170.3 | 259.6 |
| Resveratrol | — | 263.1 | 342.6 |
| Carbendazim | — | 124.3 | 219.7 |
| Fluopyram | — | 117.9 | 223.5 |

both strains. Also, the anti-fungal activity of the compounds containing hydrophilic groups was better compared to that bearing lipophilic groups (**20b** vs. **20f**) (Table 5).

Similarly, a research group⁴⁶ reported the synthesis of oxadiazole–stilbene hybrids and evaluated their efficacy against phytopathogenic fungi. The synthesis method was the same as in the previous study.⁴⁴ Compounds **21a** and **21b** exhibited superior anti-fungal activity to that of resveratrol. Also, moving the OCH₃ group from the 2'-position of **21c** to the 3'-position on the phenyl ring in **21d** increased the activity. Moreover, the presence of hydrophilic groups resulted in higher activity compared to the lipophilic groups (**21e** vs. **21f**). Compound **21b** with a pyridine ring in the 4'-position on the phenyl ring showed stronger activity than compound **21g** with a pyridine ring in the 3'-position. This finding showed that the position of the nitrogen atom in the pyridine ring may play an important role in activity. Also, the compounds containing EWG and EDG showed equal activity (*e.g.*, **21c** and **21f**) (Table 6).

Wen *et al.*⁴⁷ synthesized 1,3,4-oxadiazole–thiophene-based stilbene compounds and assessed their anti-fungal activity. In the previous study, the method of synthesized compounds was explained.⁴⁴ Compound **22a** exhibited higher activity compared to resveratrol but was weaker than carbendazim and fluopyram against *B. cinerea* and *C. lagenarium*. In addition, increasing the substitution on the phenyl ring displayed the maximum activity (*e.g.*, **22b** and **22c**) against different strains. Furthermore, among the compounds with EWG in the 4'-position on the phenyl ring, compound **22d** with a Br atom exhibited better activity compared to **22c** having a Cl atom and **22e** with an F atom in the same position against both strains. It seems that increasing the atom size improved the activity. Furthermore, the presence of the EDG in the 4'-position on the phenyl ring

Table 8 Chemical structures of resveratrol analogues



| Compound | R ₁ | R ₂ | R ₃ | R ₄ | R ₅ | R ₆ | MIC (μg mL ⁻¹) | | | Inhibition percent (%) | | | | |
|-------------|----------------|------------------|----------------|------------------|----------------|------------------|----------------------------|----------------|--------------|------------------------|-----------------------|----------------|--------------|------------------|
| | | | | | | | <i>S. aureus</i> | <i>E. coli</i> | <i>AtolC</i> | <i>P. vulgaris</i> | <i>S. typhimurium</i> | <i>E. coli</i> | <i>AtolC</i> | <i>S. aureus</i> |
| 23a | H | Br | H | OH | H | OH | 25 | >100 | 25 | >80 | >80 | — | 90 | >80 |
| 23b | H | H | H | OH | H | OH | 100 | >100 | 100 | >80 | >80 | — | 90 | >80 |
| 23c | H | OH | H | OH | H | OCH ₃ | 100 | >100 | 100 | 40 | 40 | 40 | — | — |
| 23d | H | OH | H | H | OH | H | — | — | — | — | — | — | — | — |
| 23e | H | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 23f | H | OCH ₃ | H | OCH ₃ | OH | OCH ₃ | — | — | — | — | — | — | — | — |
| 23g | H | OH | H | OCH ₃ | H | OCH ₃ | 25 | >100 | 25 | — | — | — | 90 | — |
| 23h | OH | OH | H | OH | OH | H | — | — | — | — | — | — | — | — |
| 23i | OH | OH | H | OH | H | OH | — | — | — | — | — | — | — | — |
| 23j | — | — | — | — | — | — | 10 | >100 | 10 | — | — | — | 80 | — |
| Resveratrol | — | — | — | — | — | — | 100 | >100 | 100 | — | — | — | — | — |



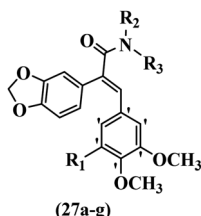
demonstrated greater activity than EWG in the same position (e.g., **22f** and **22d**) against *P. cubensis*. In addition, the anti-fungal activity of hydrophilic groups showed better activity than that of lipophilic groups (**22f** vs. **22c**) (Table 7).

Singh *et al.*⁴⁸ reported the anti-bacterial activity of resveratrol structural analogues. Compared to other bacteria tested, resveratrol was more effective against the enteric bacteria *P. vulgaris* and *S. typhimurium*. Compounds **23a** and **23b** exhibited higher inhibition than resveratrol, while compound **23c** exhibited comparable activity against *P. vulgaris*, *S. typhimurium*, and *E. coli*. The other compounds showed lower activity than resveratrol against *P. aeruginosa*. The compounds that were impressive against Gram-negative bacteria were similarly impressive against Gram-positive bacteria (compounds **23a** and **23b** against *S. aureus*). In the case of **23d–f**, no anti-bacterial activity was observed (wild-type or $\Delta tolC$ *E. coli*). Compounds **23g** and **23j** were also ineffective against wild type *E. coli*, while their activity was comparable to **23a** and **23b** against $\Delta tolC$, the two analogues that were most active against wild-type *E. coli*. Also, the presence of a Br atom in the 4'-position on phenyl ring **23a** showed excellent activity against *S. aureus* compared to **23b**, which was unsubstituted. The antibacterial activity of

compound **23c** with an OH group in the 3-position on the phenyl ring was lower than that of **23g** having an OCH₃ group in the same position against *S. aureus*. The inhibitory activity of stilbenes against *S. aureus* reiterated the fact that analogues **23a**, **23g**, and **23h** were more potent than resveratrol against *S. aureus*, while **23b** and **23c** showed comparable activity to resveratrol. When the OH groups in the molecule were replaced with acetoxy or methoxy groups, a significant reduction in anti-bacterial activity was observed (resveratrol vs. compounds **23e** or **23f**). This showed the importance of the OH group for the antibacterial activity. However, increasing the number of OH groups did not result in better antibacterial activity (resveratrol vs. **23h** with OH groups in the 3'- and 4'-positions on the phenyl ring or **23i** having OH groups in the 3'- and 5'-position on phenyl ring). The presence of an OH group in the 4'-position on the phenyl ring did not have a significant effect on the activity or inactivity of the molecule (**23b**, **23d**, and **23h**). However, it is worth noting that the best molecules in the series (**23a–c**, **23g**, and **23j**, as well as resveratrol) had an OH group in the 4'-position on the phenyl ring. Partially changing the OH group to other groups resulted in an improvement in antibacterial activity (resveratrol vs. **23a** and **23c** or **23g**). The findings showed

Table 9 Structures of 1,3-benzodioxole–stilbene derivatives

| Compound | R ₁ | R ₂ | R ₃ | Fungicidal activity (%) | | | |
|--------------|------------------|----------------|----------------|--------------------------|-----------------------|-----------------------|------------------|
| | | | | <i>G. theae-sinensis</i> | <i>A. tenuis</i> Nees | <i>F. graminearum</i> | <i>R. solani</i> |
| 27a | H | H | | <10 | <40 | 0 | <10 |
| 27b | H | H | | <10 | <20 | <20 | <20 |
| 27c | H | H | | <20 | <10 | 0 | 0 |
| 27d | OCH ₃ | H | | <20 | <20 | <20 | <20 |
| 27e | OCH ₃ | H | | <30 | <30 | <20 | <20 |
| 27f | OCH ₃ | H | | <30 | <30 | <10 | <10 |
| 27g | OCH ₃ | H | | <10 | <20 | <30 | <20 |
| Piperine | — | — | — | 74 | 55 | <30 | 62 |
| Azoxystrobin | — | — | — | 69 | 55 | 64 | 55 |



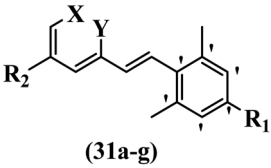
that the lipophilic groups had better activity than the hydrophilic groups (Table 8).

Song *et al.*²¹ synthesized and assessed the fungicidal activity of 1,3-benzodioxole-stilbene derivatives. Compound **27a** showed the highest activity against *G. theae-sinensis*, *A. tenuis* Nees, *F. graminearum*, and *R. solani*. This analogue was stronger than piperine and azoxystrobin, but it showed lower activity compared to piperine against *F. graminearum*. Overall, the derivatives showed low inhibitory activity against all the tested strains, while the inhibition rates of the derivatives against most fungi of the tested fungi were not greater than 20%. Replacing propylsulfane linked to an amide moiety in **27a** with methyl-4-(methylthio)butanoate in **27b** showed lower activity against *A. tenuis* Nees. Also, the presence of an OCH₃ group in the 3'-position on the phenyl ring compared to no substitution increased the fungicidal activity (*e.g.*, **27c** and **27d**) against *A. tenuis* Nees, *f. graminearum*, and *R. solani*. Also, hydrophilic groups (*e.g.*, **27e**) and lipophilic groups (*e.g.*, **27f**) are suitable to improve the fungicidal activity against *G. theae-sinensis* and *A. tenuis* Nees. In addition, the presence of cycloalkane and aromatic rings linked to an amide moiety had the same effect

on the activity (**27g** vs. **27d**) against *A. tenuis* Nees and *R. solani* (Table 9).

Hrast *et al.*⁴⁹ described azastilbene derivatives as mur ligase inhibitors and anti-bacterial agents and evaluated the inhibition of four mur ligase subgroups (MurC, MurD, MurE, and MurF). Compound **31a** was the most potent against subgroups MurD, MurE, and MurF. Compound **31b** showed the highest activity against the MurC subgroup among the compounds. In addition, the lipophilic group in **31b** displayed higher activity than the hydrophilic group in **31c** against all the mur ligases. Most of the stilbene derivatives demonstrated poor anti-bacterial activity against both *E. coli* and *S. aureus*. This could be attributed to their low target activity or poor penetration into the bacterial cytoplasm. However, replacing oxazole linked to a pyridine ring on the 4-position phenyl ring in **31c** with imidazole linked to a pyridine ring in same position of **31d** resulted in the highest anti-bacterial activity against *S. aureus* and *E. coli*. Also, the presence of hydrophilic groups resulted in better activity than lipophilic groups against both strains (**31d** and **31b**). Compound **31e** with an OCH₃ group in the 2'-position on the phenyl ring exhibited higher anti-bacterial activity

Table 10 Chemical structures of azastilbene derivatives



| Compound | X | Y | R ₁ | R ₂ | Inhibition percent (%) | | | | MIC (mM) | |
|------------|---|---|----------------|----------------|------------------------|------|------|------|------------------|----------------|
| | | | | | MurC | MurD | MurE | MurF | <i>S. aureus</i> | <i>E. coli</i> |
| 31a | C | N | | | 23 | 73 | 55 | 84 | >0.25 | >0.25 |
| 31b | N | C | | | 56 | 70 | 46 | 58 | >0.25 | >0.25 |
| 31c | N | C | | | 44 | 45 | 32 | 44 | 0.125 | >0.25 |
| 31d | N | C | | | 42 | 47 | 10 | 40 | 0.031 | 0.25 |
| 31e | N | C | | | 35 | 42 | 33 | 0 | 0.125 | >0.25 |
| 31f | N | C | | | 15 | 23 | 21 | 18 | >0.25 | >0.25 |
| 31g | N | C | | | 30 | 30 | 37 | 25 | 0.25 | >0.25 |



Table 11 Structures of *E/Z*-stilbene derivatives

| Compound | <i>E/Z</i> | R | R ₁ | IC ₅₀ (μg mL ⁻¹) | |
|--------------------|------------|------------------|----------------|--|------|
| | | | | A549 | Col2 |
| (33a-h, 35a,b) | | | | | |
| 33a | Z | OCH ₃ | | 0.01 | 0.01 |
| 33b | Z | OCH ₃ | | 0.2 | 0.3 |
| 33c | <i>E</i> | H | | 0.8 | 0.8 |
| 33d | <i>E</i> | H | | 0.8 | 0.9 |
| 33e | Z | OCH ₃ | | 2.1 | 2.6 |
| 33f | Mix | H | | >20 | >20 |
| 33g | Mix | H | | 3.2 | 7.2 |
| 33h | <i>E</i> | OCH ₃ | | 4.7 | 1.6 |

Table 11 (Contd.)

| Compound | <i>E/Z</i> | R | R ₁ | IC ₅₀ (μg mL ⁻¹) | |
|--------------------|------------|---|----------------|--|------|
| | | | | A549 | Col2 |
| (33a-h, 35a,b) | | | | | |
| 35a | — | H | | 2.6 | 5.1 |
| 35b | — | H | | >20 | >20 |
| Resveratrol | <i>E</i> | — | — | 6.9 | 18.7 |
| Oxyresveratrol | <i>E</i> | — | — | >20 | >20 |

compared to compound **31f** having an OCH₃ group in the 3'-position on the phenyl ring and **31g** with an OCH₃ group in the 4'-position on the phenyl ring against *S. aureus* and *E. coli*. It seems that changing the substitution on different positions of the phenyl ring had a positive effect on the anti-bacterial activity (the 2-position showed higher activity than the 4- and 3-positions on the phenyl ring) (Table 10).

3. Anti-cancer activity

Despite the huge effort to develop novel therapies, cancer remains the leading cause of death worldwide. One of the traditional and commonly used methods for cancer treatment is chemotherapy, which targets specific proteins and cellular structures or processes.⁵⁰

Resveratrol as an anti-cancer agent reduces angiogenesis and induces apoptosis *via* the suppression of VEGF and FGF-2.⁵¹ Piceatannol and pterostilbene, stilbene natural derivatives, are remarkably more potent than resveratrol against cancer cell lines.⁵² CA-4, a *Z*-stilbenoid analogue, is a strong inhibitor of tubulin polymerization, resulting in cancer cell death.⁵³ In many experimental models *in vitro* and *in vivo* both *Z*- and *E*-stilbene analogues showed anti-cancer activity but with diverse mechanisms. Some *Z*-isomers of methoxylated stilbenes and their derivatives revealed higher antimetastatic or antiproliferative activity than their *E*-isomers; however, the *E*-isomer of resveratrol displayed higher antiproliferative activity. Moreover, they isomerize during storage, administration, and metabolism in



liver microsomes.^{54,55} *Z*- and *E*-stilbene analogues have been studied for their cytotoxicity and anti-tubulin activities. The analysis of the results a wide range of stilbene analogues showed that the *Z*-isomer was useful for cytotoxicity and anti-mitotic activity. Tamoxifen, a stilbene analogue, is used for the treatment of some types of breast cancer.⁵³

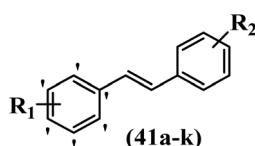
Lee *et al.*¹⁷ synthesized stilbene analogues and evaluated their cytotoxicity. *Z*-33a and b showed the highest cytotoxicity activity among the compounds. These compounds were stronger than resveratrol and oxyresveratrol against the A549 and Col2 cell lines. Especially, compound 33a having OCH₃ and Br groups in the 4- and 4'-positions on the phenyl ring exhibited approximately 600-times and 1800-times, respectively, more potent cytotoxicity than resveratrol. In the *E*-isomers, the presence of an extra OCH₃ group in 33c showed comparable activity to 33d. Also, replacing the aromatic ring of 33a with a hetero-aromatic ring in 33b and 33e decreased the activity. In the *Z/E*-isomers, moving the OCH₃ group from the 5'-position in 33f to the 6'-position on the phenyl ring in 33g increased the cytotoxicity. Based on the findings, the *Z*-isomers were more potent than their corresponding *E*-isomers (*e.g.*, 33a and 33h). In addition, adding an OCH₃ group to the phenyl ring (35a vs. 35b) reduced the cytotoxicity (Table 11).

Lion *et al.*⁵⁶ synthesized hydroxylated *E*-stilbenes and assessed their anti-tumor and apoptosis-inducing activity. Compounds 41a and 41b showed the highest activity among the compounds and resveratrol against MDA-MB-468 and HCT-116. Also, changing the position of the OH group in 41b from the 2- to 3- and 4-positions on the phenyl ring in 41c and 41d reduced the activity against both cell lines, respectively. Similarly, the compounds having EWG and lipophilic groups showed better activity than that having EDG and hydrophilic groups (*e.g.*, 41e

vs. 41f). Furthermore, the extra OCH₃ group in the 5'-position on the phenyl ring of compound 41g caused a slight improvement in activity compared to 41h. This result showed that increasing the number of substitutes on the phenyl ring had a positive effect on activity. Substitution on the phenyl ring resulted in higher activity compared to compound with no substitution (*e.g.*, 41i and 41j). With the exception of the relatively insensitive 41k, the percentage of apoptotic sub-G1/0 MDA-MB-468 cells following drug treatment was higher in all the stilbenes than in resveratrol. Following treatment with compounds 41a, 41e, and 41j, the highest percentage of cells was observed to be in early apoptosis. The induction of apoptosis was again associated with the anti-proliferative activity in MDA-MB-468 cells, particularly for the relatively potent compounds 41j and 41a. Particularly, compound 41j had a much higher percentage of cells in early apoptosis than resveratrol but a much lower percentage than camptothecin. Based on the findings, the presence of EDG and lipophilic groups resulted in the highest apoptosis activity (Table 12).

Pettit *et al.*⁴¹ evaluated *Z/E*-CA-4 derivatives for their neoplastic activity. Among the compounds, *Z*-42a showed the highest cytotoxicity activity against the BXP-3, SK-N-SH, SW-1736, NCI-H460, DU-145, and FADU cell lines. In the *Z*-isomers, replacement of the OH group in the 3'-position on the phenyl ring of CA-4 with NO₂, N(CH₃)₂, or Br groups in compounds 42b–d decreased their potency, respectively. In addition, the presence of hydrophilic groups improved the activity compared to lipophilic groups (42e and 42f). The replacement of the bulky group, such as OSO₂CH₃ in 42e, instead of OH in 42g reduced the activity. Likewise, the replacement of pyrrolidinyl in the 3'-position on the phenyl ring with piperidinyl in the same position resulted in better activity

Table 12 Chemical structures of hydroxylated *E*-stilbenes



| Compounds | R ₁ | R ₂ | GI ₅₀ (μM) | | Induced percent (%) |
|--------------|------------------------|----------------|-----------------------|------------|---------------------|
| | | | HCT-116 | MDA-MB-468 | Apoptosis |
| 41a | 3,5-diOCH ₃ | 3-OH | 43.1 | 0.96 | 20 |
| 41b | 3,4-diF | 2-OH | 15.6 | 1.1 | — |
| 41c | 3,4-diF | 3-OH | 36.0 | 1.6 | — |
| 41d | 3,4-diF | 4-OH | 18.1 | 19.1 | — |
| 41e | 2-F | 4-OH | 38.5 | 2.8 | 10 |
| 41f | 2-OCH ₃ | 4-OH | 51.3 | 3.3 | — |
| 41g | 3,5-diOCH ₃ | 2-OH | 21.3 | 2.5 | — |
| 41h | 3-OCH ₃ | 2-OH | 58.0 | 3.1 | — |
| 41i | H | 3-OH | 57.4 | 7.8 | — |
| 41j | 2-OCH ₃ | 3-OH | 42.3 | 2.7 | 15 |
| 41k | H | 2-OH | 58.1 | 24.9 | 4 |
| Resveratrol | — | — | 49.6 | 41.1 | 4 |
| Camptothecin | — | — | — | — | 37 |



(**42h** vs. **42i**) against the BXPC-3, SK-N-SH, SW-1736, NCI-H460, DU-145, and FADU cell lines. In the *E*-isomers, replacement of the NO₂ group in the 3'-position on the phenyl ring in **42j** with Br in the same position of **42k** increased the activity against P-388, BXPC-3, SK-N-SH, DU-145, and FADU. Also, replacing the OCH₃ group with an OH group in the 4'-position on the phenyl ring (*Z/E*-**42l**) resulted in a remarkable decrease (about 100-times) in activity. Subsequently, the compounds were tested for their ability to inhibit tubulin protein. Compound **42d** was as active as CA-4, while **42b** and **42e** were about half as active. The *Z*-isomers with bulkier substituents at the 3'-position on the phenyl ring were much less active as inhibitors of assembly (*e.g.*,

42f; Cl, **42g**; SO₃CH₃ and **42m**; CO₂NC₄H₈Cl₂ showed minor or no inhibitory activity). Nevertheless, *Z*-**42n** having an O(CH₂)₃OH group in the 3'-position on the phenyl ring showed better activity than **42o** with 1*H*-imidazol-1-yl in the 3'-position on the phenyl ring. Alternatively, **42p** having *N*-pyrrolyl in the 3'-position on the phenyl ring showed weaker inhibitory activity compared to **42o** and **42n**. This suggests that the aromatic substituent dominated the steric effect that restricts the stilbene-tubulin interaction indirectly based on the inactivity of **42f-i**, **42q-t**, and **42m**. Surprisingly, the more effective tubulin inhibitor (**42o**) had little cytotoxicity, whereas the less effective **42p** was highly cytotoxic in four of the seven cell lines tested. *E*-

Table 13 Structures of *Z/E*-CA-4 derivatives

| Compound | <i>E/Z</i> | R ₁ | R ₂ | GI ₅₀ (μg mL ⁻¹) | | | | | | | IC ₅₀ (μM) | |
|--------------------|------------|------------------|-------------------------------------|---|---------|---------|---------|----------|---------|---------|-----------------------|--|
| | | | | P-388 | BXPC-3 | SK-N-SH | SW1736 | NCI-H460 | DU-145 | FADU | Tubulin | |
| | | | | | | | | | | | | |
| 42a | <i>Z</i> | OCH ₃ | NH ₂ | >0.010 | 0.00043 | 0.00023 | 0.00080 | 0.00033 | 0.00033 | 0.00053 | — | |
| 42b | <i>Z</i> | OCH ₃ | NO ₂ | 2.4 | 0.029 | 0.014 | 0.0067 | 0.0038 | 0.047 | 0.047 | 2.6 | |
| 42c | <i>Z</i> | OCH ₃ | N(CH ₃) ₂ | 0.9 | 0.015 | 0.010 | 0.80 | 0.4 | 0.11 | 0.090 | 1.1 | |
| 42d | <i>Z</i> | OCH ₃ | Br | 0.16 | 0.007 | 0.002 | 0.034 | 0.033 | 0.027 | 0.0058 | — | |
| 42e | <i>Z</i> | OCH ₃ | | 0.195 | 0.045 | 0.028 | 0.28 | 0.14 | 0.32 | 0.069 | 2.8 | |
| 42f | <i>Z</i> | OCH ₃ | | 2.9 | 2.7 | 2.0 | 4.7 | 3.7 | 3.4 | 4.6 | >40 | |
| 42g | <i>Z</i> | OCH ₃ | | 2.87 | 2.7 | 3.0 | 1.0 | 0.42 | 0.59 | 0.41 | >40 | |
| 42h | <i>Z</i> | OCH ₃ | | 0.421 | 2.0 | 0.22 | 0.60 | 0.34 | 0.35 | 0.49 | >40 | |
| 42i | <i>Z</i> | OCH ₃ | | 0.348 | >10.0 | 1.6 | 5.1 | 3.3 | 3.4 | 4.2 | >40 | |
| 42j | <i>E</i> | OCH ₃ | NO ₂ | >10 | >10 | 7.3 | 2.8 | >0.0 | >10 | 3.8 | — | |
| 42k | <i>E</i> | OCH ₃ | Br | 3.08 | 0.34 | 0.40 | 10.8 | 0.36 | 0.46 | 11.4 | 31 | |
| 42l | <i>E</i> | OCH ₃ | O(CH ₂) ₃ OH | 4.9 | >10.0 | 8.1 | 11.6 | >10.0 | 4.5 | 2.3 | — | |
| 42m | <i>Z</i> | OCH ₃ | | 0.074 | 2.8 | 0.14 | 0.72 | 0.37 | 0.31 | 0.15 | >40 | |
| 42n | <i>Z</i> | OCH ₃ | O(CH ₂) ₃ OH | 0.63 | 0.26 | 0.18 | 0.38 | 0.37 | 0.43 | 0.63 | 6.5 | |
| 42o | <i>Z</i> | OCH ₃ | | 19.0 | 0.82 | 0.31 | 1.5 | 0.56 | 1.5 | 0.67 | 7.6 | |
| 42p | <i>Z</i> | OCH ₃ | | 0.0232 | 2.3 | 0.0064 | 4.9 | 0.0033 | 0.56 | 0.0030 | 20 | |
| 42q | <i>Z</i> | OCH ₃ | | 0.523 | >10.0 | 0.21 | 0.64 | 0.34 | 0.38 | 0.47 | >40 | |
| 42r | <i>Z</i> | OCH ₃ | | 0.255 | >10.0 | 1.5 | 1.1 | 3.3 | 3.4 | 1.1 | >40 | |
| 42s | <i>Z</i> | OCH ₃ | | 0.634 | 2.9 | 0.22 | 0.97 | 0.41 | 0.40 | 0.53 | >40 | |
| 42t | <i>Z</i> | OCH ₃ | | 1.60 | >10.0 | 2.8 | >10.0 | 3.4 | 4.1 | 2.9 | >40 | |
| 42u | <i>E</i> | OH | OH | 4.49 | 5.0 | 5.5 | >10.0 | 4.9 | 6.3 | 3.2 | 14 | |
| Combretastatin A-4 | <i>E</i> | — | — | 0.0029 | 0.23 | 0.00025 | 0.00061 | 0.00035 | 0.00072 | 0.00045 | 33 | |
| Combretastatin A-4 | <i>Z</i> | — | — | 0.0026 | >0.1 | 0.00026 | 0.00026 | 0.00056 | 0.00076 | 0.00065 | 1.2 | |



Table 14 Structures of aza-stilbene derivatives

(45a-l)

| Compound | <i>n</i> | R ₁ | R ₂ | R ₃ | R ₄ | pIC ₅₀ (μM) c-RAF/MEK/ERK | c-RAF |
|----------|----------|-------------------|-------------------------------|-------------------------------|----------------|---|-------|
| 45a | 10 | | — | — | OH | 8.4 | 0.004 |
| 45b | 5 | | — | — | H | 7.9 | — |
| 45c | 3 | COOH | — | — | — | 8.2 | — |
| 45d | 4 | CONH ₂ | — | — | OH | 6.8 | — |
| 45e | 4 | CONH ₂ | — | — | — | 8.1 | — |
| 45f | 4 | | — | — | | 7.0 | — |
| 45g | 4 | — | CH ₃ | CH ₃ | — | 6.6 | — |
| 45h | 1 | — | C ₂ H ₅ | C ₂ H ₅ | — | 4.6 | — |
| 45i | 4 | — | CH ₃ | Cl | — | 7.1 | — |
| 45j | 4 | — | Cl | Cl | — | 6.6 | — |
| 45k | 1 | — | CH ₃ | H | — | 5.5 | — |
| 45l | 1 | — | Cl | H | — | 5.7 | — |

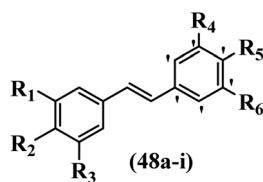
42k showed comparable activity to *E*-CA-4. *E*-42u with an OH group in the 3'- and 4-positions on the phenyl ring showed more than double activity. The results showed that the *Z*-isomers were stronger than the *E*-isomers (Table 13).

McDonald *et al.*⁵⁷ synthesized aza-stilbenes and assessed their c-RAF inhibitor activity. Compound 45a showed the highest c-RAF inhibitory activity. In addition, removing the OH group in the 4'-position on the phenyl ring of 45a produced 45b, which had a slight effect on the enzyme activity. Also, the compounds that had a hydrogen-bond acceptor or donor in the 3-position on the pyridine ring, such as compounds 45c with a COOH group, 45d having a CONH₂ group, or 45b with tetrazole, showed higher activity against MEK/ERK. Moreover, replacing the OH group in the 4'-position on the phenyl ring with *N*-methyl carbamate caused a remarkable increase in c-RAF inhibitory activity (45d vs. 45e). Also, replacement of the compounds containing tetrazole (45a and 45b) with a 2-pyridine ring (45f) resulted in only a minor decrease in c-RAF activity. According to the primary findings, the aza-stilbene scaffold with the two CH₃ groups in the 2'- and 6'-positions on the phenyl ring in compound 45g was kept to obtain potent c-RAF inhibitors. Also, compound 45h was 100-times less potent than 45g, demonstrating a size limitation. In addition, changing the CH₃ group in 45i with a Cl atom in the 2-position on the phenyl ring of 45j resulted in a compound that was equal to 45g. Likewise, the presence of CH₃ or Cl in the 2'-position on the phenyl ring,

45k and 45l, showed 10-times less activity than 45g. When only one of CH₃ group was swapped with a Cl atom on the phenyl ring, as in 45h, the activity increased by about 3-times compared to 45g (Table 14).

Gossiau *et al.*¹⁹ reported that *E/Z*-stilbene polyphenols induced *p53*-independent apoptosis and rapid perinuclear mitochondrial clustering. Among the *Z*-isomers, 48a and 48b were more than 1000-times effective compared to resveratrol against the WI38VA cell line. Furthermore, the addition of an NH₂ group at the 3'-position on the phenyl ring in 48b resulted in lower activity compared to 48c. However, attaching an NO₂ group in the 3'-position on the phenyl ring in 48d reduced the activity compared to 48c. In the *E*-isomers, the addition of an NO₂ group in the 3'-position on phenyl ring decreased activity (48e vs. 48f). As well, appending OCH₃ group in 3'-position on the phenyl ring in 48g drastically reduced the anti-proliferative activity compared to 48f. The addition of an OCH₃ group in the 4'-position on the phenyl ring enhanced its anti-proliferative activity at least 10-times (48h vs. 48i). Attaching an OCH₃ group in the 4'-position enhanced the activity for both the *Z*- and *E*-isomers by at least 4-times (48i vs. 48f, and 48c vs. 48a). Also, the hydrophilic group showed less activity compared to the lipophilic group (*e.g.*, 48j and 48i). In addition, the presence of a Br atom in the 4'-position on the phenyl ring in 48k resulted in better activity than no substitution in 48l. *E*-48f, the most potent derivative in this series, was 200-times less potent than *Z*-



Table 15 Synthetic compounds of *E/Z*-stilbene

| Compound | <i>E/Z</i> | R ₁ | R ₂ | R ₃ | R ₄ | R ₅ | R ₆ | IC ₅₀ (μM) WI38VA |
|-------------|------------|------------------|------------------|------------------|------------------|------------------|----------------|---------------------------------|
| 48a | <i>Z</i> | OCH ₃ | OCH ₃ | OCH ₃ | — | OCH ₃ | — | 0.02 |
| 48b | <i>Z</i> | OCH ₃ | — | OCH ₃ | NH ₂ | OCH ₃ | — | 0.05 |
| 48c | <i>Z</i> | OCH ₃ | — | OCH ₃ | — | OCH ₃ | — | 0.03 |
| 48d | <i>Z</i> | OCH ₃ | — | OCH ₃ | NO ₂ | OCH ₃ | — | 0.5 |
| 48e | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | NO ₂ | OCH ₃ | — | 10 |
| 48f | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | — | OCH ₃ | — | 2 |
| 48g | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | OCH ₃ | OCH ₃ | — | — |
| 48h | <i>E</i> | OCH ₃ | OCH ₃ | — | — | — | — | — |
| 48i | <i>E</i> | OCH ₃ | — | OCH ₃ | — | OCH ₃ | — | 25–50 |
| 48j | <i>E</i> | OH | — | OH | — | OH | — | 50 |
| 48k | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | — | Br | — | 25–50 |
| 48l | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | — | — | — | 80 |
| Resveratrol | <i>E</i> | — | — | — | — | — | — | 50 |

48a. The *Z*-isomer analogues were the most potent *E*-isomer analogues, with IC₅₀ values comparable to or better than resveratrol against WI38VA cells. Apoptosis revealed that **48a** activated caspase 3/7 in the WI38VA cells. Similar to **48f**, this compound activated apoptosis in the transformed cells. The findings recommend that mitochondrial clustering can happen in the absence of a main change in microtubule dynamics, implying that microtubule depolymerization is not directly responsible for perinuclear mitochondrial clustering. **48a** and **48f** both inhibited the growth of wild-type and *p53*-null cells. These findings imply that the proapoptotic activity of **48a** and **48f** against cancer cells was not dependent on *p53* (Table 15).

Simoni *et al.*⁵⁸ designed stilbene-based derivatives and assessed their anti-tumor activity. Compound **52a** was the most active compound among the derivatives, while it showed weaker or equal activity compared to vincristine, colchicine, and CA-4 against UCI-101, SNU-423, MDA-MB231, and MiaPaCa-2. Most of the compounds showed weak cytotoxicity against SNU-423, MDA-MB231, and MiaPaCa-2. In addition, compound **52b** with *N*-methylpyrrole in the 3- and 4-positions on the phenyl ring exhibited weaker cytotoxicity activity compared with **52a** having NH₃⁺Cl⁻ and OCH₃ groups in the same position against MDA-MB231 and MiaPaCa-2. Also, replacement of the OCH₃ in **52a** with an OH group in the 3'-position on the phenyl ring in **52c** decreased the activity by more than 10-times against the UCI-101 and MDA-MB23 cell lines. In contrast, when the OCH₃ group in the 3-position on the phenyl ring was replaced by bulkier substituents, *i.e.*, ethoxy or isopropoxy groups, as in compounds **52d** and **52e** compared to **52a**, respectively, the activity decreased. Moreover, compound **52f**, with a 2-hydroxyethyl group in the 3'-position on the phenyl ring, still retained its activity. However, the addition of a carboxyl group, as in

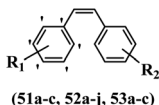
compound **52g** against UCI-101, completely eliminated its activity, representing unequivocally that the environment cannot tolerate excessive hydrophilicity. Also, the replacement of the OCH₃ group with *N*-methylpyrrole in the 3'- and 4'-positions on the phenyl ring dramatically reduced the activity for **52h** against UCI-101. This result showed that a hydrophobic environment is required for activity. The derivatives with an indole or imidazole ring in **51a**, **51b**, and **51c** showed equal activity against this cell line. Shifting the nitrogen atom in the indole ring from the 1-position in compound **52b** to the 3-position in compound **52i** resulted in weaker activity against UCI-101. It is worth noting that **52b** and **52i** have diverse biological effects, therefore demonstrating a favorable interaction for the CH₃ group in compound **52b**. Among compounds **53a–c**, only **53a** with carbamic acid morpholin-4-yl-ethyl ester in the 3-position on the phenyl ring was active in suppressing the growth of tumor cells, which was 170-times less active than stilbene **52a**. Both **53b** with morpholin-4-ylethylureahydrochloride salt in the 3-position on the phenyl ring and **53c** with carbamic acid (2-hydroxyethoxy)ethoxyethyl ester in the same position were not capable of causing remarkable inhibition of cell growth, demonstrating that their activity is lower than **53a**. This could be because compounds **53a–c** were not changed into the active form, stilbene **53a**, under the tissue culture conditions. The tubulin inhibitory activity of the four derivatives **52** that changed substitution in the 3-position on the phenyl ring showed potency following the order of **52f** > **52c** > **52d** > **52j**. Compound **52c**, in particular, has the second-best tubulin inhibitory activity but significantly weaker cytotoxic activity compared to derivatives **52f**, **52d**, and **52j**. When selective second-ring derivatives were tested for tubulin inhibitory activity (**52b** > **52i** > **52a**), their cytotoxicity followed the order of **52b** > **52i** > **52a**. As a result, in addition to tubulin depolymerization, stilbene derivatives may have other mechanisms for inducing cell death (Table 16).

Moon *et al.*⁵⁹ synthesized resveratrol derivatives and evaluated their cytotoxicity activity. Compounds **59a** and **59b** were the most potent compounds among them against the XF-498, SK-OV-3, HCT-15, A-549, and SK-MEL-2 cell lines. Furthermore, compound **59a** showed the highest activity in all the cell lines in terms of cytotoxicity. However, none of the compounds exhibited stronger activity than adriamycin against all the cell lines. Besides, compound **59c** with *N*-(4-benzylpiperidine) carbonyl in the 4'-position on the phenyl ring exhibited higher activity than **59d** having *N*-(4-methylpiperidine)carbonyl in the same position against SK-MEL-2, A-549, and HCT-15. However, compound **59d** was inactive against these cell lines. Also, replacement of the aromatic ring in **59e** with a heteroaromatic ring in **59f** decreased the activity against A549, SK-OV-3, SK-MEL-2, and XF-498. In addition, replacing *N*-decylaminocarbonyl in **59g** in the 4'-position with *N*-cyclohexylaminocarbonyl in **59b** on the same position enhanced the activity against all the cell lines (Table 17).








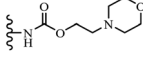
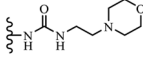
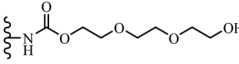
Belluti *et al.*⁶⁰ synthesized stilbene-coumarin hybrids and evaluated their cytotoxicity. Compounds **62a** and **62b** displayed higher activity compared to resveratrol against the H460, A431, and JR8 cell lines and were the most potent compounds among



Table 16 Chemical structures of stilbene-based derivatives



(51a-c, 52a-j, 53a-c)

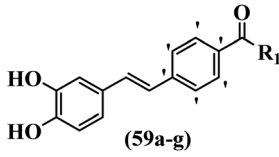
| Compound | R ₁ | R ₁ | R ₂ | R ₂ | IC ₅₀ (nM) | | | |
|------------------|---|--------------------|--|---|-----------------------|---------|-----------|----------|
| | | | | | UCI-101 | SNU-423 | MDA-MB231 | MiaPaCa2 |
| 51a | 3-OCH ₃ | 3-OCH ₃ |  | — | 250 | 700 | 250 | 200 |
| 51b | 3-OCH ₃ | 3-OCH ₃ |  | — | 250 | 700 | 250 | 200 |
| 51c | 3-OCH ₃ | 3-OCH ₃ |  | — | 260 | 1000 | 800 | 800 |
| 52a | 3-OCH ₃ | 3-OCH ₃ | 3-OCH ₃ | 4-NH ₃ ⁺ Cl ⁻ | 30 | 30 | 30 | 40 |
| 52b | 3-OCH ₃ | 3-OCH ₃ |  | — | 40 | 30 | 80 | 80 |
| 52c | 3-OH | 3-OCH ₃ | 3-OCH ₃ | 4-NH ₃ ⁺ Cl ⁻ | 800 | 2000 | 800 | 700 |
| 52d | 3-OCH ₂ CH ₃ | 3-OCH ₃ | 3-OCH ₃ | 4-NH ₃ ⁺ Cl ⁻ | 80 | — | — | — |
| 52e | 3-OCH(H ₃ C) ₂ | 3-OCH ₃ | 3-OCH ₃ | 4-NH ₃ ⁺ Cl ⁻ | 100 | — | — | — |
| 52f | 3-O(H ₂ C) ₂ OH | 3-OCH ₃ | 3-OCH ₃ | 4-NH ₃ ⁺ Cl ⁻ | 150 | 200 | 80 | 180 |
| 52g | 3-OCH ₂ COOH | 3-OCH ₃ | 3-OCH ₃ | 4-NH ₂ | >10.000 | — | — | — |
| 52h |  | — | 3-OCH ₃ | NH ₂ x(COOH) ₂ | 5000 | — | — | — |
| 52i | 3-OCH ₃ | 3-OCH ₃ |  | — | 220 | — | — | — |
| 52j |  | — | 3-OCH ₃ | NH ₂ | 200 | — | — | — |
| 53a | 3-OCH ₃ | 3-OCH ₃ | OCH ₃ |  | 5000 | 5000 | — | — |
| 53b | 3-OCH ₃ | 3-OCH ₃ | OCH ₃ |  | >10.000 | — | — | — |
| 53c | 3-OCH ₃ | 3-OCH ₃ | OCH ₃ |  | >10.000 | — | — | — |
| Colchicine | — | — | — | — | 30 | 25 | 20 | 25 |
| Vincristine | — | — | — | — | 20 | 10 | 15 | 15 |
| Combretastatin A | — | — | — | — | 2 | 6 | 4 | 8 |

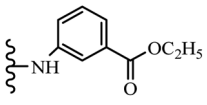
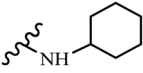
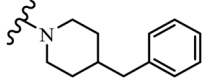
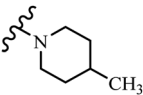
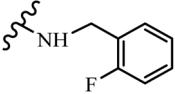
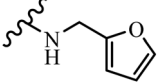
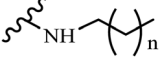
the studied compounds. All the compounds were inactive against the A431 and JR8 cell lines except **62a** and **62b**. In this series, compound **62b** appeared to be one of the most active compounds, thus presenting proof for the significance of the OCH₃ group in the 4-position on the coumarin ring as a scaffold. On moving the OCH₃ group from the 4- to 3-position on the coumarin ring in derivative **62b**, resulting in compound **62c**, a dramatic drop in potency was observed, suggesting that the 4-position insertion is also crucial. Furthermore, when the OCH₃ groups of **62b** were replaced with OH, derivative **62g** was 60-times less active than **62b** and 2-times less active than resveratrol against H460. Considering these results, the extra structural

changes were made in **62b** focusing on the phenyl ring, a significant decrease in anti-proliferative activity was detected for compound **62d** with an OCH₃ group in the 5'-position and **62e** bearing an OCH₃ group in the 2'-position on the phenyl ring. Besides, the removal of one OCH₃ group in **62b** resulted in a decrease in activity. Also, **62f** showed comparable activity to resveratrol against H460. These findings revealed that the OCH₃ groups in the 3'- and 5'-positions on the phenyl ring had an important role, and their exchange with CH₃, **62a**, showed somewhat greater potency than the corresponding molecule **62b**. Subsequently, **62b** and **62a** was investigated for inducing apoptosis. In particular, the proapoptotic effect of **62b** showed



Table 17 Chemical structures of resveratrol analogues



| Compound | R ₁ | IC ₅₀ (μM) | | | | |
|-------------|---|-----------------------|---------|----------|--------|--------|
| | | A-549 | SK-OV-3 | SK-MEL-2 | XF-498 | HCT-15 |
| 59a |  | 8.7 | 5.7 | 10.4 | 11.4 | 14.4 |
| 59b |  | 10.4 | 6.8 | 12.4 | 13.6 | 17.2 |
| 59c |  | 45.7 | 26.8 | 43.0 | 25.4 | 47.4 |
| 59d |  | — | 21.6 | — | 21.6 | — |
| 59e |  | 12.7 | 9.1 | 16.2 | 15.7 | 21.5 |
| 59f |  | 25.6 | 26.2 | 22.4 | 28.0 | 16.4 |
| 59g |  | 16.4 | 21.7 | 14.2 | 19.7 | 21.2 |
| Resveratrol | — | 36.9 | 42.6 | 41.4 | 32.1 | 35.6 |
| Adriamycin | — | 2.8 | 4.3 | 2.6 | 2.1 | 7.6 |

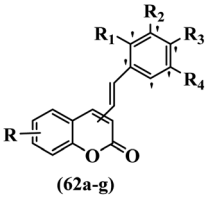
a level of apoptosis similar to that of cisplatin and substantially higher than that of resveratrol. Caspase 3 and PARP cleavage were investigated. This effect was linked to a partial cell tumor during the G2/M phase of the cell cycle. In summary, the existence of specific substituents in different positions of both moieties of the hydride compound was confirmed to be serious in discussing the anti-proliferative activity; substitutions shaped the 4-position on the coumarin ring and the 3'- and 5'-positions on the phenyl ring were revealed to be a satisfactory feature for both the anti-tumor and proapoptotic activities (Table 18).

Reddy *et al.*⁶¹ designed resveratrol-based nitrovinylstilbenes and tested their anti-mitotic and anti-tubulin activities. Compound **66a** was the most potent compound among them and showed higher activity than resveratrol against the MCF-7 cell line. However, **66a** showed weaker or equal anti-proliferative activity compared to resveratrol against the SK-N-SH, A-549, and HeLa cell lines. Compound **66b** showed higher anti-proliferative activity compared to resveratrol against MCF-

7, SK-N-SH, A549, and HeLa. Also, EDG showed better activity compared to EWG (*e.g.*, **66b** vs. **66c**) against SK-N-SH, A-549, and HeLa. Likewise, changing the dioxane ring in the 3'- and 4'-positions (**66d**) with a phenyl ring in the 4'-position on the phenyl ring (**66a**) reduced the activity against all the tested cell lines. In contrast, **66a** showed stronger activity than **66d** against the MCF-7 cell line. Furthermore, increasing the number of OCH₃ groups in different positions on the phenyl ring of **66e** resulted in lower anti-proliferative activity compared to **66f** against the tested cell lines. Also, the presence of a lipophilic group had more favorable anti-proliferative activity than a hydrophilic group on the phenyl ring (**66c** vs. **66g**) against the MCF-7, SK-N-SH, and A-549 cell lines. Compounds **66b**, **66d**, and **66g** had higher cytotoxicity activity, which correlated well with their ability to effectively inhibit tubulin. Compound **66b**, as expected, demonstrated the greatest inhibition of tubulin assembly. All the compounds were less potent than colchicine. The findings showed that the compounds inhibited tubulin assembly in the order of **66b** > **66g** > **66d**. The anti-mitotic



Table 18 Synthetic compounds of stilbene–coumarin hybrids



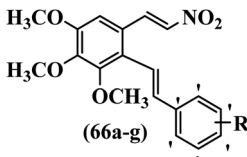
| Compound | Insertion position | IC ₅₀ (μM) | | | | | | | Induced apoptosis (%) | |
|-------------|--------------------|-----------------------|------------------|------------------|------------------|------------------|------|------|-----------------------|-----|
| | | R | R ₁ | R ₂ | R ₃ | R ₄ | H460 | A431 | | JR8 |
| 62a | 4 | 7-OCH ₃ | H | CH ₃ | H | CH ₃ | 0.29 | 3.5 | 3.5 | 32 |
| 62b | 4 | 7-OCH ₃ | H | OCH ₃ | H | OCH ₃ | 0.45 | 3.44 | 3.2 | 27 |
| 62c | 3 | 7-OCH ₃ | H | OCH ₃ | H | OCH ₃ | >10 | — | — | — |
| 62d | 4 | 7-OCH ₃ | H | OCH ₃ | OCH ₃ | OCH ₃ | >100 | — | — | — |
| 62e | 4 | 7-OCH ₃ | OCH ₃ | OCH ₃ | OCH ₃ | H | >50 | — | — | — |
| 62f | 4 | 7-OCH ₃ | H | OCH ₃ | H | H | 12.9 | — | — | — |
| 62g | 4 | 7-OH | H | OH | H | OH | 27 | — | — | — |
| Resveratrol | — | — | — | — | — | — | 12.9 | — | — | — |

effects of active compounds **66b**, **66g**, and **66d** were tested. These compounds showed higher activity in the G2/M phase of HeLa cells compared to resveratrol. Most of the cells were arrested at the G2/M phase by compounds **66b**, **66d**, and **66g**. These findings support the inhibitory activity of nitrovinylstilbene derivatives (**66b** and **66g**) against the HeLa cell line. The activation of caspase-3 by compounds **66b** and **66g** in

HeLa cells was examined. Compared to resveratrol, treatment with compound **66b** resulted in a 12-times increase in caspase-3 activity. In contrast, resveratrol did not cause a significant increase in caspase-3 activation (Table 19).

Csuk *et al.*²⁰ synthesized *E*-stilbene-based derivatives and evaluated their anti-tumor activity. Compounds **69a** and **69b** showed the highest activity against 518A2, 850C, A253, A549,

Table 19 Chemical structures of resveratrol-based nitrovinylstilbenes



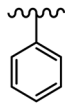
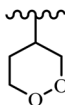
| Compounds | R | IC ₅₀ (pM) | | | | IC ₅₀ (μM) | Inhibition percent (%) | | Fold-increase in Caspase-3 |
|-------------|---|-----------------------|---------|------|------|-----------------------|------------------------|------|----------------------------|
| | | MCF-7 | SK-N-SH | A549 | HeLa | | Tubulin | G2/M | |
| 66a |  | 7.2 | 35.8 | 44.4 | — | — | — | — | |
| 66b | 4-CH ₃ | 42.5 | 12.5 | 19.0 | 4.4 | 4.27 | 66.43 | 10 | |
| 66c | 4-F | 19.0 | 18.8 | 35.9 | 12.4 | — | — | — | |
| 66d |  | 19.2 | 20.9 | 16.3 | 5.4 | 8.02 | 50.66 | — | |
| 66e | 3,4,5-triOCH ₃ | 13.2 | 60.9 | 27.1 | — | — | — | — | |
| 66f | 3,5-diOCH ₃ | 19.2 | 36.2 | 15.0 | 10 | — | — | — | |
| 66g | 4-OCH ₃ | 21.4 | 20.7 | 40.4 | 7.8 | 4.90 | 60.40 | 11.5 | |
| Resveratrol | — | 79.1 | 40.3 | 44.7 | 22.5 | — | 21.29 | — | |
| Colchicine | — | — | — | — | — | 1.96 | — | — | |





Table 20 Chemical structures of stilbene-based compounds

| Compound | IC ₅₀ (μM) | | | | | | | | | | | | | | Induced apoptosis (%) | | | | |
|------------|-----------------------|------------------|------------------|----------------|----------------|------------------|------------------|------------------|------------------|-------|-------|-------|-------|-------|-----------------------|-------|-------|-------|--------|
| | R ₁ | R ₂ | R ₃ | R ₄ | R ₅ | R ₆ | R ₇ | R ₈ | R ₉ | 518A2 | 850C | A253 | A549 | A2780 | | DLD1 | Lipo | MCF7 | NIH3T3 |
| 69a | — | OH | OCH ₃ | — | F | OCH ₃ | — | OCH ₃ | — | 0.03 | 0.03 | 0.03 | 0.03 | 0.01 | 0.04 | 0.03 | 0.06 | 0.05 | 77.3 |
| 69b | — | OH | OCH ₃ | — | F | — | OCH ₃ | F | OCH ₃ | 0.20 | 0.13 | 0.48 | 0.18 | 0.11 | 0.20 | 0.21 | 0.22 | 0.19 | 64.1 |
| 69c | — | — | OH | — | — | — | OH | — | OH | >30 | >30 | >30 | >30 | >30 | >30 | >30 | >30 | 24.22 | — |
| 69d | — | OH | OCH ₃ | — | — | OCH ₃ | — | — | OCH ₃ | 0.72 | 0.86 | 0.80 | 0.96 | 0.87 | 0.91 | 0.65 | 0.54 | 1.54 | — |
| 69e | — | OH | OCH ₃ | — | — | OCH ₃ | — | OCH ₃ | — | 1.33 | 1.33 | 1.53 | 1.80 | 1.27 | 2.00 | 1.41 | 1.64 | 2.08 | — |
| 69f | — | OCH ₃ | OCH ₃ | — | — | — | OCH ₃ | F | OCH ₃ | 18.04 | 17.72 | 15.83 | 22.16 | 23.92 | 14.95 | 16.51 | 11.20 | 6.76 | — |
| 69g | — | OCH ₃ | OCH ₃ | — | — | — | OCH ₃ | — | OCH ₃ | 2.81 | 2.46 | 2.35 | 3.04 | 2.06 | 2.86 | 2.86 | 1.89 | 3.68 | 77.1 |
| 69h | — | OH | OCH ₃ | — | F | OCH ₃ | — | — | OCH ₃ | 1.74 | 2.26 | 1.34 | 2.21 | 2.01 | 2.26 | 1.98 | 2.09 | 2.66 | 72 |
| 69i | — | OH | OCH ₃ | — | F | OH | — | — | OH | 19.43 | 16.77 | 9.88 | 15.77 | 10.47 | 18.00 | >30 | 10.63 | 21.06 | — |
| 69j | — | — | OH | — | — | OH | — | — | OH | 28.36 | 18.70 | 15.16 | 12.66 | 16.62 | 22.91 | 17.37 | 14.17 | 9.59 | — |
| 69k | OH | — | — | — | — | OH | — | — | OH | 22.00 | 24.45 | 14.53 | 19.01 | 12.42 | 18.11 | 24.07 | 13.18 | 12.38 | — |
| Tamoxifen | — | — | — | — | — | — | — | — | — | 7.62 | 11.09 | 8.92 | 9.66 | 7.77 | 4.78 | 8.64 | 7.10 | 7.26 | — |

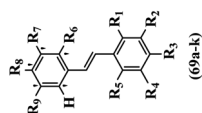


Table 21 Structures of biaryl stilbenes/ethylenes

| Compound | R | R ₁ | IC ₅₀ (μM) | | | | | Inhibition mitosis percent (%) |
|---------------------|------------------------|----------------|-----------------------|------|---------|-------|---------|--------------------------------|
| | | | A549 | Hela | SK-N-SH | DU145 | Tubulin | |
| (74a-h) (76a-h) | | | | | | | | |
| 74a | | | 6.3 | 8.7 | 8.0 | 7.3 | 6.8 | 73.02 |
| 74b | 3,4-diF | | 7.5 | 9.2 | 6.9 | 7.5 | 9.2 | 71.16 |
| 74c | 4-OCH ₃ | | 35 | 19 | 36 | 34 | — | — |
| 74d | 4-Cl | | 30 | 49 | 15 | 35 | — | — |
| 74e | H | | 36 | 26 | 11 | 51 | — | — |
| 74f | 3,4-diOCH ₃ | | 28 | 45 | 42 | 34 | — | — |
| 74g | H | | 79 | 89 | 63 | 82 | — | — |
| 74h | H | | 54 | 45 | 31 | 101 | — | — |
| 76a | | | 5.0 | 5.4 | 6.1 | 6.0 | 8.6 | 73.00 |
| 76b | 3,4-diF | | 6.5 | 5.9 | 7.5 | 6.8 | 11.2 | 70.02 |
| 76c | H | | 22 | 11 | 31 | 8 | — | — |
| 76d | | | 15 | 35 | 6 | 46 | — | — |
| 76e | H | | 17 | 42 | 34 | 36 | — | — |
| 76f | H | | 40 | 34 | 25 | 29 | — | — |
| 76g | 4-Cl | | 29 | 30 | 15 | 33 | — | — |



Table 21 (Contd.)

(74a-h) (76a-h)

| Compound | R | R ₁ | IC ₅₀ (μM) | | | | | Inhibition mitosis percent (%) |
|------------|--------------------|----------------|-----------------------|------|---------|-------|---------|--------------------------------|
| | | | A549 | Hela | SK-N-SH | DU145 | Tubulin | |
| 76h | 4-OCH ₃ | | 14 | 72 | 75 | 37 | — | — |
| Colchicine | — | — | — | — | — | — | 1.7 | 19.4 |

A2780, DLD1, Lipo, MCF-7, and NiH3T3 cell lines. These compounds were also more potent than tamoxifen. Among the compounds, **69c** exhibited the lowest activity. Switching the OCH₃ group from the 5'- to 4'-position on the phenyl ring (**69d** vs. **69e**) decreased the activity against all the tested cell lines. In addition, adding an F atom in the 4'-position on the phenyl ring compared to no substitution resulted in lower activity (**69f** vs. **69g**) against the tested cell lines. Also, changing OCH₃ with an OH group in the 2'- and 5'-positions on the phenyl ring reduced the cytotoxicity activity (**69h** vs. **69i**). It seems that lipophilic groups show higher activity than hydrophilic groups. Moreover, moving the OH group in the 4- to the 2-position on the phenyl ring showed almost equal cytotoxicity activity (e.g., **69j** and **69k**) against all the cell lines. In addition, the apoptotic activity of the compounds was almost similar to the cytotoxic activity against the A549 cell line (Table 20).

Kumar *et al.*⁶² synthesized biaryl stilbenes/ethylenes and assessed their anti-microtubule activity. Among the synthesized compounds in the first series, **74a** and **74b** exhibited the highest activity against the A549, HeLa, SK-N-SH, and DU-145 cell lines. Attaching OCH₃ (**74c**) and Cl groups (**74d**) to the 4-position on the phenyl ring compared to **74e**, which was unsubstituted resulted in lower anti-proliferative activity against the SK-N-SH cell line. In addition, an extra OCH₃ group in the 3-position on phenyl ring decreased the activity (**74c** vs. **74f**) against the HeLa and SK-N-SH cell lines. Also, the addition of a CH₃ group in the 4'-position on the phenyl ring of **74h** compared to no substitution (**74g**) enhanced the activity against the A549, HeLa, and SK-N-SH cell lines. Similarly, compounds **76a** and **76b** demonstrated the highest activity in the second series against the A549, HeLa, SK-N-SH, and DU145 cell lines. The compound with no substitution on the phenyl ring (**76c**) displayed higher activity than **76d** having a phenyl on the phenyl ring against HeLa and DU145. However, **76c** showed weaker activity than **76d** against A549 and SK-N-SH. Also, attaching a Cl group in the 4'-position on the phenyl ring compared to no substitution resulted in better activity (**76e** and **76f**). Moreover, according to the SAR studies of both series, it was concluded that the substitutions with a small size and strong electronegativity in

the 3- and 4-positions on the phenyl ring may be important for effective anti-proliferative activity (e.g., **74b** and **76b**). Also, the presence of EDG in the 4-position on phenyl showed better activity compared to EWG against A549 (**76h** vs. **76g**). The results showed that the second series exhibited stronger activity compared to the first series. Also, **74a** demonstrated the maximum inhibition of tubulin. None of the compounds showed stronger activity than colchicine. **74a**, **74b**, **76a**, and **76b** arrested the majority of the population of cells at the G2/M phase. Overall, these findings indicated that compounds **74a**, **74b**, **76a**, and **76b** inhibited tubulin polymerization more effectively than the other compounds in both series (Table 21).

Roman *et al.*⁶³ designed some *E/Z*-stilbenes and tested their anti-invasive activity. Among the synthesized compounds, *E*-**81a** and **81c** exhibited the highest activity against MCF-7/6. In both isomers, attaching substitutions in the 4'-position phenyl ring enhanced the activity (e.g., **81a** and **81c**). The *Z*-isomers showed better activity than the *E*-isomers (e.g., *Z*-**81d** and *E*-**81d**). Analogues *E*-**81e** and *Z*-**81e**, combining both decoration patterns, displayed very weak potency. Overall, the results showed that two-atom spacers are well tolerated between the aromatic moieties (Table 22).

Table 22 Structures of *E/Z*-stilbenes

(81a-e)

| Compound | <i>E/Z</i> | R ₁ | R ₂ | IC ₅₀ (μM) MCF-7/6 |
|------------|------------|---------------------------|----------------|-------------------------------|
| 81a | <i>E</i> | 4-OCH ₃ | 4-F | 0.01 |
| 81b | <i>Z</i> | 4-F | H | 0.01 |
| 81c | <i>E</i> | 4-OCH ₃ | H | 0.1 |
| 81d | <i>E</i> | 3,4,5-triOCH ₃ | H | 0.1 |
| 81d | <i>Z</i> | 3,4,5-triOCH ₃ | H | 0.01 |
| 81e | <i>E</i> | 3,4,5-triOCH ₃ | 4-F | 1 |
| 81e | <i>Z</i> | 3,4,5-triOCH ₃ | 4-F | 0 |



Centelles *et al.*⁶⁴ synthesized stilbene derivatives and evaluated their cytotoxicity and inhibitory activity against VEGF. Compound **84a** showed the highest activity against the BAE cell line among the synthesized compounds. Also, it was more potent than resveratrol. Likewise, moving the OH group in the 4'-position of compound **84a** to the 2'- or 3'-position on the phenyl ring in **84b** or **84c** resulted in lower activity against BAE. Moreover, changing the OCH₃ group in the 2'-position on the phenyl ring in **84d** with an OH group in the same position in **84b** resulted in an enhancement in activity against BAE. Further, moving the *O*-allyl moiety from 2'- to 4'-position on phenyl ring reduced activity against BAE (**85a** vs. **85b**). In addition, the cytotoxicity of all the compounds was investigated against the HT-29 cell line. Among the synthesized compounds, **85b** showed higher activity compared to resveratrol against HT-29. Moreover, compound **84a** exhibited stronger activity than **84b** and **84c**. Compound **84d** showed weaker cytotoxicity compared to **84b**. Compound **85b** had more potent activity than **85a**. According to the results, changing the position of substitution on the phenyl ring improved the cytotoxicity activity against the HT-29 and BAE cell lines (4' > 2' > 3'). Resveratrol and some stilbene analogues reduced the VEGF expression in HT-29 cells. Compounds **84b** and **85a** decreased the VEGF expression to a higher extent than resveratrol and DMSO. Replacement of the OH in the 2'-position on the phenyl ring in **84b** with an OCH₃ group in the same position in **84d** resulted in lower activity against VEGF. The results showed that hydrophilic groups displayed higher activity compared to lipophilic groups. Also, the presence of bulky groups decreased the activity against BAE and expression of VEGF. However, it increased the activity against the HT-29 cell line (Table 23).

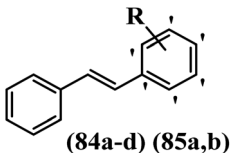
Zhang *et al.*⁶⁵ synthesized 2-hydroxylated *E*-stilbenes and assessed their anti-proliferative activity. Among the synthesized compounds, **88a** against Colo-205 and MGC80-3, **88b** against HT-29, and **88c** against MDA-468 showed the highest activity. Changing the Br atom in the 4'-position on the phenyl ring (**88d**) with CH₃ (**88e**), OH (**88f**), and CN (**88g**) groups reduced

cytotoxicity activity against all the cell lines. It seems that the compounds with a lipophilic group compared to a hydrophilic group showed stronger cytotoxicity activity. Also, the presence of an extra OCH₃ group in the 4'-position on the phenyl ring in **88c** enhanced the cytotoxicity activity compared to **88h** against MDA-468 and MGC80-3. In addition, moving the OCH₃ group from the 3- to 4-position on phenyl improved the cytotoxicity activity (**88i** vs. **88h**) against MDA-468 and MGC80-3. Besides, the compounds with substitution on the phenyl ring showed better cytotoxicity activity than no substitution (**88j** vs. **88a**) against all the cell lines. In addition, the compounds containing EWG exhibited the higher activity compared to EDG (*e.g.*, **88e** and **88d**) (Table 24).

Morris *et al.*⁶⁶ tested the anti-tumor properties of methylated *Z*-resveratrol. Compounds **89e** and **89h** showed lower activity than **89d** against the proliferation of B16-F10. However, the inhibition potency of *Z*-**89f** and **g** was slightly higher than that of **89d**. These results indicated that *Z*-tetra-methoxy inhibited motility more effectively than *Z*-tri- or penta-methoxy. However, isomers of **89a-c** showed no visible activity on β -tubulin expression. It was discovered that **89d** reduced the expression of tubulin in B16-F1 cells, while **89a-c** exhibited no activity. Compared to DMSO, all the tested *Z*-isomers showed a dramatic decrease in intracellular tubulin protein, and in the case of **89f**, the level of expression was below the detectable limit. When compounds **89a-d** were compared, **89d** was the most effective in inhibiting the proliferation of B16-F10 cells, B16-F1 cells, and melanocytes. These findings imply that these cells respond differently to the anti-proliferative effects of **89d**. The *Z*-poly-methoxy compounds were created to inhibit cell proliferation compared to DMSO-treated cells, with **89d** being the most potent inhibitor, while analogues **89e**, **89f**, and **89h** were significantly less potent. It is worth noting that neither the *E*-isomer (**89a**) nor any of the counterpart *trans*-poly-methoxystilbenes (**89c** and **89i-l**) had a significant effect on B16-F10 cell proliferation. In addition, the present lipophilic groups showed higher activity compared to hydrophilic groups (**89d** vs. **89b**). Also, the *Z*-isomers exhibited superior activity in comparison to their corresponding *E*-isomers (Table 25).

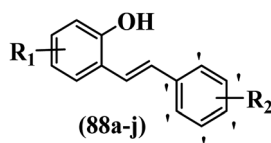
Scherzberg *et al.*⁶⁷ evaluated resveratrol derivatives against tumor cells. The method for the synthesis of resveratrol derivatives **90a** and **90b** was the same as in the reported study.²⁶ Compared to *E*-resveratrol, *Z*-**90a** showed 100-times higher anti-proliferative activity against HT-29. Compound *Z*-**90a** inhibited HepG2 cell growth. *E*-Resveratrol exhibited lower activity for HepG2 cells compared to Caco-2. In contrast to Caco-2, the IC₅₀ value for *Z*-**90a** in HepG2 is the highest. However, in both proliferation assays, *Z*-**90a** had significantly lower IC₅₀ values than *E*-resveratrol. These findings are comparable to that obtained in the Caco-2 cell line. In comparison to the results in tumor cell lines, *Z*-**90a** only had moderate effects on HUVEC cell growth. Compound *Z*-**90a** exhibited no cytotoxic effect on CaCo-2, HT-29, HepG2 cells, and HUVECs. Another distinction was revealed by the cell cycle analysis, where both *E/Z*-resveratrol arrested cells in the S-phase, whereas *E/Z*-**90a** arrested cells in the G2/M phase. According to the results, lipophilic groups

Table 23 Synthetic compounds of stilbene



| Compound | R | IC ₅₀ (μM) | | IC ₅₀ (ng mL ⁻¹) |
|-------------|--------------------|-----------------------|-------|---|
| | | BAE | HT-29 | VEGF |
| 84a | 4-OH | 33.6 | 34.6 | — |
| 84b | 2-OH | 107 | 112 | 19 |
| 84c | 3-OH | 91.7 | 127 | — |
| 84d | 2-OCH ₃ | 152 | 42.8 | 39 |
| 85a | 2-Oallyl | 313 | 55 | 20 |
| 85b | 4-Oallyl | >400 | 23 | — |
| Resveratrol | — | 48 | 110 | 30 |



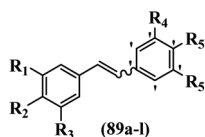
Table 24 Synthetic structures of 2-hydroxylated *E*-stilbenes

| Compound | R ₁ | R ₂ | IC ₅₀ (μM) | | | |
|-------------|--------------------|---------------------------|-----------------------|---------|-------|---------|
| | | | Colo-205 | MDA-468 | HT-29 | MGC80-3 |
| 88a | 4-OCH ₃ | 3,4,5-triOCH ₃ | 5.3 | 5.3 | 9.7 | 0.035 |
| 88b | 5-Br | 3,5-diOCH ₃ | 16.4 | 6.1 | 9.5 | 3.3 |
| 88c | 3-OCH ₃ | 3,4,5-triOCH ₃ | — | 2.6 | — | 1.1 |
| 88d | H | 4-Br | 21.1 | 7.4 | 14.4 | — |
| 88e | H | 4-CH ₃ | — | 21.9 | 22.9 | — |
| 88f | H | 4-OH | — | — | 33.5 | — |
| 88g | H | 4-CN | — | — | — | 3.1 |
| 88h | 3-OCH ₃ | 3,5-diOCH ₃ | — | — | — | — |
| 88i | 4-OCH ₃ | 3,5-diOCH ₃ | — | 8.4 | — | 0.8 |
| 88j | H | H | — | 19.3 | — | — |
| Resveratrol | — | — | 23.5 | 45.2 | 87.2 | 42 |

displayed better activity than hydrophilic groups incorporation in BrdU (Table 26).

Yan *et al.*⁶⁸ synthesized benzoselenazole-stilbene hybrids and assessed their cytotoxicity activity. Among the analogues, **95a** showed the highest activity, and it was more active than resveratrol and ebselen against the Bel-7402, A549, HeLa, and MCF-7 cell lines. Also, moving the OCH₃ group from the 4'-position in **95b** to the 5'-position on the phenyl ring in **95c** decreased the anti-proliferative activity against the tested cell lines. In addition, the extra OCH₃ group in the 5'-position on

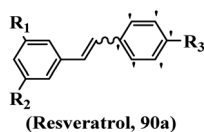
the phenyl ring of **95b** produced **95d**, which showed reduced activity against the A549 and HeLa cell lines. However, **95b** and **95d** showed equal activity against the Bel-7402 and MCF-7 cell lines. When the number of OCH₃ groups on phenyl ring decreased, the activity decreased markedly (**95c** vs. **95e**). This exhibited that the OCH₃ group is essential for an anti-cancer effect. Consequently, it can be concluded that the compound with two OCH₃ groups, particularly at the 3'- and 4'-positions on the phenyl ring, was active. In contrast, the findings revealed that the OCH₃ groups in the 4- and 5-positions on the phenyl

Table 25 Structures of methylated *E/Z*-resveratrol

| Compound | <i>E/Z</i> | R ₁ | R ₂ | R ₃ | R ₄ | R ₅ | R ₆ | Inhibition percent (%) | | |
|------------|------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------------------|-----------------------|------------------|
| | | | | | | | | B16-F10, B16-F1, melanocytes | Proliferation B16-F10 | Motility B16-F10 |
| 89a | <i>E</i> | OH | H | OH | H | OH | H | — | — | — |
| 89b | <i>Z</i> | OH | H | OH | H | OH | H | — | — | — |
| 89c | <i>E</i> | OCH ₃ | H | OCH ₃ | H | OCH ₃ | H | — | — | — |
| 89d | <i>Z</i> | OCH ₃ | H | OCH ₃ | H | OCH ₃ | H | 75 | 71 | — |
| 89e | <i>Z</i> | OCH ₃ | OCH ₃ | H | H | OCH ₃ | H | — | 45 | 50–60 |
| 89f | <i>Z</i> | OCH ₃ | H | OCH ₃ | OCH ₃ | OCH ₃ | H | — | 45 | 80–90 |
| 89g | <i>Z</i> | OCH ₃ | OCH ₃ | OCH ₃ | H | OCH ₃ | H | — | 66 | 80–90 |
| 89h | <i>Z</i> | OCH ₃ | OCH ₃ | OCH ₃ | H | OCH ₃ | OCH ₃ | — | 45 | 50–60 |
| 89i | <i>E</i> | OCH ₃ | OCH ₃ | H | H | OCH ₃ | H | — | — | — |
| 89j | <i>E</i> | OCH ₃ | OCH ₃ | H | H | OCH ₃ | OCH ₃ | — | — | — |
| 89k | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | H | OCH ₃ | H | — | — | — |
| 89l | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | OCH ₃ | H | OCH ₃ | — | — | — |
| DMSO | — | — | — | — | — | — | — | 100 | 100 | — |



Table 26 Chemical structures of resveratrol derivatives



| Compounds | <i>E/Z</i> | R ₁ | R ₂ | R ₃ | IC ₅₀ (μM) | | | |
|-------------|------------|------------------|------------------|------------------|-----------------------|--------|-------|--------------------|
| | | | | | HT-29 | CaCo-2 | HepG2 | BrdU incorporation |
| Resveratrol | <i>E</i> | OH | OH | OH | 115.9 | 190.2 | 110.7 | 100 |
| Resveratrol | <i>Z</i> | OH | OH | OH | — | — | — | >200 |
| 90a | <i>Z</i> | OCH ₃ | OCH ₃ | OCH ₃ | 0.115 | 0.145 | 0.473 | 0.2–0.5 |
| 90a | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | — | — | — | 5–20 |

ring had a negative effect on the activity of **95f** against all the tested cell lines compared to the other compounds. When the group in the 4-position on the phenyl ring changed to F or Cl atoms, the anti-proliferative activity remarkably increased (**95g** and **95a**). The findings exhibited that the *E*-isomer stilbene scaffold was favorable for cytotoxic activity compared to the corresponding *Z*-isomers (**95b** vs. **98**). Compared with **95b**, the anti-proliferative activity of compound **102** was significantly lower (<10-times), which strongly demonstrated that the benzoselenazole-stilbene hybrids were beneficial for the activity. The *in vitro* inhibition of thioredoxin reductases (TrxR) was tested using the compounds. Compound **95b** revealed the highest activity among the compounds, which was also better than that of ebselen. Compounds **95c** and **95d** exhibited better cell growth inhibition effects compared to **95e** and **95h**. Compounds **95g**, **95a**, **95i**, and **95j**, which have halogen atoms on the phenyl ring, exhibited the highest TrxR inhibitory activity. However, compound **95f**, which demonstrated relatively good inhibitory activity against TrxR, showed less cell growth inhibition. Compound **102**, which is characterized by the absence of a selenium atom, revealed no activity, further demonstrating the requirement of selenium in the derivatives. Furthermore, treatment with compound **95b** resulted in significant cell cycle arrest at the G2/M phase. These findings showed that the compounds could halt cell cycle progression at the mitosis stage. The cell apoptosis assay results showed that resveratrol and compound **95b** caused significant cell apoptosis. Compound **95b** effectively induced cell apoptosis in Bel-7402 cells, eventually leading to cell death according to the data (Table 27).

Mahdavi *et al.*⁶⁹ designed *N*-substituted 2-arylquinazolinones and tested their cytotoxicity activity. Among the synthesized compounds, **109a** against MCF-7 and T-47D and **109b** against MDA-MB-231 showed the best cytotoxicity activity. They were also more potent than etoposide against MCF-7, MDA-MB-231, and T-47D. In addition, the compounds containing an aliphatic ring showed increased activity compared to that having an aromatic ring (*e.g.*, **109c** vs. **109d**) against MCF-7, MDA-MB-231, and T-47D. Likewise, *N*-alkyl groups were more active than *N*-aryl and *N*-benzyl groups. Compound **109e** with *N*-cyclopentyl

was inactive against all the tested cell lines, while **109f** with *N*-propyl showed activity against MCF-7. Most of the *N*-alkyl quinazolinones had similar sensitivity in all the tested cell lines. However, in the case of compound **109g**, the sensitivity of MCF-7 was significantly lower than that of MDA-MB-231 and T-47D. The IC₅₀ values of compounds **109d** and **109h–l** indicated that the aryl or benzyl substituents were not favorable for cytotoxicity; however, compound **109k** with a 4-methylbenzyl moiety in the 3-position of quinazolinones showed mild activity against all the tested cell lines. Additionally, there is a similar difference against MCF-7 in **109g** and **109a** having isobutyl and *sec*-butyl groups, respectively. This could be because connecting diverse bonds of *N*-isobutyl and *N*-*sec*-butyl groups to the 3-position of quinazolinones caused diverse steric effects on the 2-aryl ring. Consequently, compounds **109a** and **109c** were tested compared to etoposide for the detection of apoptosis in the MDA-MB-231 and MCF-7 cell lines. Compounds **109c** and **109a** reduced the cell viability and induced apoptosis in MCF-7 and MDAMB-231 cells. Although the screened derivatives caused some necrosis in the treated cells, the results showed that **109a** and **109c** induced apoptosis in MDA-MB-231 cells. The ability of compound **109c** to induce apoptosis in MDA-MB-231 cells was comparable to that of etoposide. The results also revealed that the percentage of MCF-7 cells undergoing apoptosis after exposure to compounds **109a** and **109c** was higher than MDA-MB-231. According to the findings, compounds **109c** and **109a** exhibited cytotoxic activity in the MDA-MB-231 and MCF-7 cell lines *via* apoptosis (Table 28).

Penthala *et al.*⁷⁰ synthesized and evaluated the cytotoxicity of heteroaromatic analogues of resveratrol. Compound **112a** was the most potent compound against most of the tested cell lines. Also, hydrophilic groups exhibited higher cytotoxicity activity than lipophilic groups against most of the tested cell lines (**112a** vs. **112b**) (Table 29).

Centelles *et al.*⁷¹ synthesized nitrogen-containing heterocyclic stilbene analogues and tested their inhibitory activity against hTERT, VEGF, and c-Myc. Among them, compounds **115a** against HT-29, **115b** against MCF-7, and **118a** and **118b** against HEK-293 showed the highest cytotoxicity activity. These compounds also exhibited stronger activity than resveratrol



Table 27 Structures of benzoselenazole–stilbene hybrids

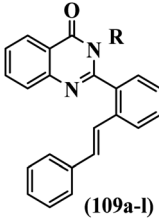
(95a-j, 98, 102)

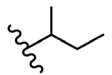
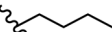
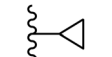
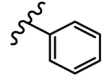
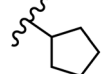
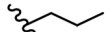
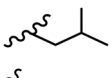
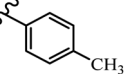
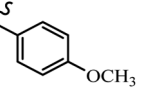
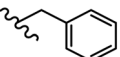
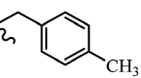
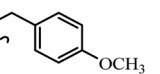
| Compound | <i>E/Z</i> | R ₁ | R ₂ | R ₃ | R | IC ₅₀ (μM) | | | | Inhibition percent (%) | | | Induced apoptosis (%) |
|-------------|------------|------------------|------------------|------------------|---|-----------------------|------|------|-------|------------------------|------|-------|-----------------------|
| | | | | | | Bel-7402 | A549 | HELA | MCF-7 | TrxR | TrxR | G2/M | |
| 95a | <i>E</i> | OCH ₃ | H | OCH ₃ | | 0.79 | 0.52 | 0.23 | 0.47 | — | 36.4 | — | — |
| 95b | <i>E</i> | OCH ₃ | OCH ₃ | H | | 1.01 | 1.53 | 1.52 | 3.37 | 3.10 | — | 44.23 | 53.4 |
| 95c | <i>E</i> | OCH ₃ | H | OCH ₃ | | 3.49 | 3.73 | 3.80 | 7.78 | 8.27 | — | — | — |
| 95d | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ | | 1.11 | 3.11 | 5.67 | 3.97 | 5.78 | — | — | — |
| 95e | <i>E</i> | OCH ₃ | H | H | | 13.2 | 10.4 | 7.34 | 9.62 | 12.8 | — | — | — |
| 95f | <i>E</i> | OCH ₃ | H | OCH ₃ | | 25.4 | 52.6 | 31.6 | 88.9 | 7.53 | — | — | — |
| 95g | <i>E</i> | OCH ₃ | H | OCH ₃ | | 0.99 | 1.22 | 0.64 | 0.51 | — | 36.6 | — | — |
| 95h | <i>E</i> | H | H | H | | 12.4 | 23.8 | 35.7 | 24.8 | — | 22.4 | — | — |
| 95i | <i>E</i> | OCH ₃ | H | OCH ₃ | | — | — | — | — | — | 31.2 | — | — |
| 95j | <i>E</i> | OCH ₃ | OCH ₃ | H | | 6.13 | 6.95 | 12.0 | 16.9 | — | 38.4 | — | — |
| 98 | <i>Z</i> | OCH ₃ | OCH ₃ | H | | 36.1 | 43.0 | 28.4 | 56.3 | 9.62 | — | — | — |
| 102 | <i>E</i> | OCH ₃ | OCH ₃ | H | | >10 | >10 | >10 | >10 | — | — | — | — |
| Resveratrol | — | — | — | — | — | 50.7 | >100 | 47.9 | >100 | — | 26.1 | — | — |
| Ebselen | — | — | — | — | — | 68.2 | >100 | 78.5 | >100 | 8.54 | — | — | — |

against the HEK-293, MCF-7, and HT-29 cell lines. Most of the compounds showed weaker cytotoxicity than resveratrol. Likewise, moving the OCH₃ group from the 3'-position in **115a** to the 4'-position on the phenyl ring in **115c** reduced the cytotoxicity against all the tested cell lines. Also, moving the nitrogen atom from the 3-position to the 2-position in the pyridine ring mitigated the cytotoxicity activity (**115d** vs. **115e**) against the HT-29 and MCF-7 cell lines. However, **115e** had stronger activity than **115d** against the HEK-293 cell line. Also, the conversion of pyridine ring **115f** to pyrimidine ring **115g** reduced the cytotoxicity against the three cell lines. In addition, the lipophilic groups showed greater cytotoxicity activity compared to

hydrophilic groups (*e.g.*, **115a** and **118c**) against all the tested cell lines. Also, the HT-29 tumoral cell line was used to study the effect of stilbene derivatives on VEGF secretion and VEGF gene inhibition. Compounds **115h** and **115c** demonstrated significant capability to inhibit VEGF expression. Surprisingly, they showed significantly higher activity than resveratrol. Compound **115a**, the most potent compound, also revealed considerable inhibitory activity against VEGF expression. Compounds **115c** and **115h**, which had the strongest inhibitory activity against VEGF expression, showed significantly lower ability to inhibit VEGF gene expression. In contrast, compound **118c**, which was previously only weakly active in inhibiting



Table 28 Chemical structures of *N*-substituted 2-arylquinazolinones


| Compound | R | IC ₅₀ (μM) | | | Induce apoptosis | |
|-----------|---|-----------------------|------------|-------|------------------|------------|
| | | MCF-7 | MDA-MB-231 | T-47D | MCF-7 | MDA-MB-231 |
| 109a |  | 3.8 | 4.9 | 3.6 | 26.46 | 16.55 |
| 109b |  | 9.8 | 4.0 | 7.9 | — | — |
| 109c |  | 5.3 | 5.5 | 6.8 | 25.88 | 22.4 |
| 109d |  | 44.9 | >100 | >100 | — | — |
| 109e |  | >100 | >100 | >100 | — | — |
| 109f |  | 29.4 | >100 | >100 | — | — |
| 109g |  | 23.3 | 6.9 | 9.3 | — | — |
| 109h |  | >100 | >100 | >100 | — | — |
| 109i |  | >100 | >100 | >100 | — | — |
| 109j |  | >100 | >100 | >100 | — | — |
| 109k |  | 24.7 | 23.8 | 28.2 | — | — |
| 109l |  | >100 | >100 | >100 | — | — |
| Etoposide | — | 7.6 | 10.3 | 8.9 | — | — |

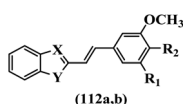
VEGF expression, had the strongest ability to inhibit VEGF gene expression. Compounds **115i**, **115d** and **115h** all had the same capacity to inhibit hTERT gene expression. The remaining compounds, including **115a**, had marginal activity that is slightly lower than the control. However, the trend of activities for inhibiting *c-Myc* gene expression was demonstrated to be noticeably diverse. Compounds **115i**, **115d**, and **115h** showed significant inhibitory activity on hTERT gene expression, which

were much less active in inhibiting *c-Myc* gene expression. Compounds **115a**, **115c**, **118c**, and **118d**, which previously had such poor activity against hTERT gene expression, were much more active against *c-Myc* gene expression, mainly **115a** and **118d**, which had the same activity with resveratrol (Table 30).

Centelles *et al.*⁷² synthesized resveratrol analogues and assessed their cytotoxicity. Analogue **121a** showed the highest cytotoxicity and it was also better than resveratrol against the



Table 29 Structures of heteroaromatic analogues of resveratrol



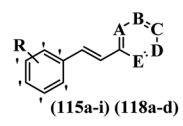
| Compound | X | Y | R ₁ | R ₂ | GI ₅₀ (μM) | | | | | | | | | | | | | | | |
|-------------|----|---|------------------|------------------|-----------------------|-------|--------|----------|-------|-------|-------|------------|---------|-------------|-------|-------|--|--|--|--|
| | | | | | K562 | SR | HOP-92 | NCI-H226 | HT29 | KM12 | U251 | MDA-MB-435 | OVCAR-3 | NCI/ADR-RES | A498 | UO-31 | | | | |
| 112a | N | S | OCH ₃ | OCH ₃ | 0.041 | 0.036 | 0.036 | 0.245 | 0.038 | 0.072 | 0.088 | 0.024 | 0.069 | 0.106 | 0.041 | 0.376 | | | | |
| 112b | CH | S | OCH ₃ | OCH ₃ | 0.088 | 0.120 | 0.322 | 0.442 | 0.234 | 0.213 | 0.338 | 0.036 | 0.224 | 0.070 | 0.213 | 0.513 | | | | |

HEK-293, MCF-7, and HT-29 cell lines. Moreover, moving the OH group from the 2'- to 3'-position on the phenyl ring enhanced the cytotoxicity (**121b** vs. **121c**) against HT-29 and HEK-293. Likewise, shifting the OCH₃ group from the 4- in **121d** to 2-position on the phenyl ring in **121e** resulted in lower cytotoxicity against all the tested cell lines. Also, the comparison of compound **121f** having an NH₂ group in the 4-position, **121g** bearing an NH₂ group in the 3-position, and **121h** having an NH₂ group in the 2-position on the phenyl ring showed that **121f** was more potent than **121g** and **121h** against HT-29. In addition, moving the NH₂ group from the 2- to 3-position on the phenyl ring resulted in stronger activity (e.g., **121i** and **121j**) against the MCF-7 and HEK-293 cell lines. In addition, the presence of lipophilic groups compared to hydrophilic groups enhanced the cytotoxicity activity (**121k** vs. **121l**) against all the tested cell lines. Also, EWG in **121m** showed higher activity compared to EDG in **121f** against MCF-7. According to the findings, different substitutions in the diverse positions of both

phenyl rings had a positive effect on the cytotoxicity (4 > 2 > 3). In addition, compound **121a** showed ability to suppress the expression of h-TERT and c-Myc genes. Compound **121o** was the most active compound among the amide stilbenes. Among the amino stilbenes, those with a methoxy group (**121i**, **121j**, **121n**, and **121a**) exhibited greater activity than that with a hydroxy group (Table 31).

Srivastava *et al.*⁷³ synthesized quinolino-stilbene derivatives and evaluated their cytotoxicity activity. Among the synthesized *E/Z*-compounds, **127a** showed the highest activity against the HeLa, MCF-7, MDA-MB231, MDA-MB468, and 184B5 cell lines. Most of the compounds exhibited better activity compared to paclitaxel, camptothecin, and chloroquine. In the *Z*-isomers, replacing the CF₃ group with an F atom in the 4'-position on the phenyl ring reduced the activity by 2–5 times (**127b** vs. **127c**) against five cell lines. In addition, moving the CF₃ group from the 4'- in **127d** to 3'-position on the phenyl ring in **127a** improved the activity by 2-times. However, adding an OCH₃

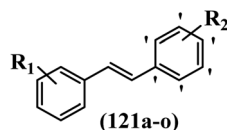
Table 30 Chemical structures of nitrogen-containing heterocyclic stilbene analogues



| Compound | R | A | B | C | D | E | IC ₅₀ (μM) | | | Inhibition percent (%) | | | |
|-------------|--------------------|---|---|---|---|---|-----------------------|-------|---------|------------------------|-----------|------------|------------|
| | | | | | | | HT-29 | MCF-7 | HEK-293 | VEGF protein | VEGF gene | hTERT gene | c-Myc gene |
| 115a | 3-OCH ₃ | — | — | N | — | — | 44 | 88 | 56 | 52 | 95 | 95 | 50 |
| 115b | 2-OCH ₃ | N | — | — | — | — | 274 | 1.7 | 175 | — | — | — | — |
| 115c | 4-OCH ₃ | — | — | N | — | — | 61 | 142 | 114 | 42 | 91 | — | 63 |
| 115d | 3-OCH ₃ | — | N | — | — | — | 104 | 128 | 123 | — | — | 57 | 71 |
| 115e | 3-OCH ₃ | N | — | — | — | — | 223 | 204 | 68 | — | — | — | — |
| 115f | 4-OCH ₃ | — | N | — | — | — | 299 | 62 | 213 | — | — | — | — |
| 115g | 4-OCH ₃ | — | N | — | N | — | >500 | >500 | 259 | — | — | — | — |
| 115h | 2-OCH ₃ | — | — | N | — | — | 76 | 100 | 85 | 37 | 54 | 54 | 64 |
| 115i | 4-OCH ₃ | N | — | — | — | — | 114 | 147 | 199 | — | — | 52 | 87 |
| 118a | 4-OH | — | — | N | — | — | 168 | 16 | 13 | — | — | — | — |
| 118b | 2-NH ₂ | — | — | N | — | — | 255 | 383 | 13 | — | — | — | — |
| 118c | 3-NH ₂ | — | — | N | — | — | 168 | 235 | >500 | 93 | 48 | — | 58 |
| 118d | 4-NH ₂ | — | — | N | — | — | 100 | 20.6 | 41 | — | — | — | 49 |
| Resveratrol | — | — | — | — | — | — | 150 | 71 | 31 | 78 | 65 | 57 | 51 |



Table 31 Synthetic derivatives of stilbene



| Compounds | R ₁ | R ₂ | IC ₅₀ (μg mL ⁻¹) | | | | % gene expression | |
|-------------|--|--------------------|---|--------|---------|------|-------------------|-------|
| | | | HT-29 | MCF-7 | HEK-293 | VEGF | hTERT | c-Myc |
| 121a | 4-NH ₂ | 4-OCH ₃ | 0.0036 | 0.0021 | 0.012 | 67 | 48 | 69 |
| 121b | 4-OH | 2-OH | 22 | 21 | 17.5 | — | — | — |
| 121c | 4-OH | 3-OH | 6.9 | 23 | 1.1 | — | — | — |
| 121d | 4-OCH ₃ | 4-OH | 17.4 | 11.3 | 3.9 | — | — | — |
| 121e | 2-OCH ₃ | 4-OH | 24 | 19 | 41 | — | — | — |
| 121f | 4-NH ₂ | H | 4.4 | 16 | 11.4 | 24 | 65 | 46 |
| 121g | 3-NH ₂ | H | 12.9 | 14 | 84 | — | — | — |
| 121h | 2-NH ₂ | H | 17 | 1.4 | 1.3 | — | — | — |
| 121i | 2-NH ₂ | 3-OCH ₃ | 21.2 | 6.1 | 0.5 | 100 | 35 | 79 |
| 121j | 3-NH ₂ | 3-OCH ₃ | 19.6 | 34 | 16 | 23 | 100 | 34 |
| 121k | 3-NH ₂ | 3-OCH ₃ | 16.3 | 23 | 11 | — | — | — |
| 121l | 3-NH ₂ | 2-OH | 30.4 | 24.7 | 96 | 38 | 52 | 37 |
| 121m | 3-NHCO(CH ₂) ₁₀ CH ₃ | H | >100 | 3.5 | 11.6 | — | — | — |
| 121n | 3-NH ₂ | 2-OCH ₃ | 25.3 | 38.7 | 45 | 67 | 52 | 45 |
| 121o | 2-NHCO(CH ₂) ₁₀ CH ₃ | H | 2.5 | 12 | 16 | 37 | 53 | 45 |
| Resveratrol | — | — | 34.1 | 16.1 | 7.1 | 65 | 57 | 51 |

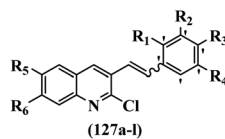
group in the 3'-position of the phenyl ring did not have any discernible effect on the anti-proliferative activity when combined with a CF₃ group in the 3-position (127a vs. 127e). Moreover, an extra CF₃ group on the phenyl ring had a negative effect on the activity (127d vs. 127f). Also, the presence of CF₃ groups at the 3'- and 5'-positions resulted in 5–10 times better activity than the 2'- and 4'-positions (127f vs. 127g) and (127h vs. 127i) against the HeLa cell line. The addition of a Cl atom at the 4-position of the phenyl ring reduced the activity by 5-times (127f vs. 127j) against all the tested cell lines, whereas the addition of an OCH₃ group in the 3-position on the phenyl ring improved the activity by 2-times (127f vs. 127h). A methylenedioxy group on the phenyl ring reduced the activity by 10-times against HeLa, MCF-7, MDA-MB231, MDA-MB468, and 184B5 (127a vs. 127k). The SAR studies showed that a CF₃ group in the 3'- or 4'-position on the phenyl ring is the best position for anti-proliferative activity. Although an OCH₃ group in the 4-position on the phenyl ring is tolerable, it did not contribute to an enhancement in activity. According to the findings, the stereochemistry and positions of various functional groups are likely to play vital roles in the cytotoxicity. *E*-127l with an F atom in the 4'-position on the phenyl ring was very active against the MDA-MB468 cell line and moderately active against the MCF7 cell line. However, it had a low level of activity against HeLa, MDA-MB231, and 184B5. Besides 127l, the *Z*-stilbene derivatives had higher activity and better anti-cancer effect than the *E*-stilbene derivatives. Compounds 127a and 127l inhibited cell cycle progression at the mitosis and S-phase, respectively, eventually leading to apoptosis. Compound 127a appeared to impede normal G2-M progression, eventually leading to cell

death. In MDA-MB231 metastatic breast cancer cells, compound 127a caused a similar pattern of G2/M arrest and DNA fragmentation. Compound 127a did not exhibit significant G2/M arrest or DNA fragmentation against MCF10A. In comparison to DMSO, compound 127l significantly increased the S-phase population in MDA-MB-468 cells. According to the data, 127l causes DNA damage, which leads to S-phase arrest, and eventually cell death (Table 32).

Kachhadia *et al.*⁷⁴ described the synthesis of stilbene derivatives and evaluated their anti-cancer activity. Compound 131a exhibited the highest inhibitory activity against histone deacetylase (HDAC). Moreover, the secondary amide in 131b slightly reduced the activity compared with the tertiary amide in 131c. In addition, the presence of cyclopropyl in compound 131d increased the activity by 5-times against HDAC compared to 131b. Also, changing the cyclopropyl ring in 131d to cyclooctyl in 134e significantly reduced the activity. Moreover, the HDAC activity decreased when the substitution changed from morpholine to pyrrolidine (*e.g.*, 131f and 131g). Also, aromatic substitutions such as phenyl in 131h or benzyl in 131i decreased the activity. Other substitutions, such as benzyloxy 131j and cyclopentyloxy 131k, also showed excellent HDAC inhibitory activity. Likewise, replacing the OCH₃ group in the 3-position on the phenyl ring of 131l with a Cl atom of 131m in the same position enhanced the activity. In addition, the F atom at the 3'-position of the phenyl ring had a positive effect on the activity when combined with an OCH₃ group at the 4'-position on the phenyl ring (131n vs. 131o). In the compounds having a heteroaryl ring, the indol-3-yl in compound 138a had the highest activity, while the other rings significantly reduced the HDAC



Table 32 Structures of quinolino-stilbene derivatives



| Compound | <i>E/Z</i> | R ₁ | R ₂ | R ₃ | R ₄ | R ₅ | R ₆ | IC ₅₀ (μM) | | | | | Inhibition percent (%) |
|--------------|------------|-----------------|-----------------|-----------------|-----------------|--------------------|----------------|-----------------------|-------|-----------|-----------|-------|------------------------|
| | | | | | | | | HeLa | MCF-7 | MDA-MB231 | MDA-MB468 | 184B5 | S-phase |
| 127a | <i>Z</i> | H | CF ₃ | H | H | H | H | 2.85 | 3.53 | 3.75 | 3.70 | 6.15 | 17 |
| 127b | <i>Z</i> | H | H | CF ₃ | H | H | Cl | 12.64 | 6.45 | 13.55 | 16.13 | 26.40 | — |
| 127c | <i>Z</i> | H | H | F | H | H | Cl | 38.62 | 16.89 | 42.56 | 10.91 | 26.89 | — |
| 127d | <i>Z</i> | H | H | CF ₃ | H | H | H | 4.22 | 4.26 | 5.36 | 7.38 | 7.94 | — |
| 127e | <i>Z</i> | H | CF ₃ | H | H | OCH ₃ | H | 3.03 | 2.78 | 3.28 | 3.91 | 5.58 | — |
| 127f | <i>Z</i> | H | CF ₃ | H | CF ₃ | H | H | 6.78 | 7.46 | 10.13 | 10.52 | 13.67 | — |
| 127g | <i>Z</i> | CF ₃ | H | CF ₃ | H | H | H | 35.89 | 10.45 | 41.76 | — | — | — |
| 127h | <i>Z</i> | H | CF ₃ | H | CF ₃ | OCH ₃ | H | 4.14 | 4.70 | 4.47 | 5.79 | 7.97 | — |
| 127i | <i>Z</i> | CF ₃ | H | CF ₃ | H | OCH ₃ | H | >50 | >50 | >50 | >50 | >50 | — |
| 127j | <i>Z</i> | H | CF ₃ | H | CF ₃ | H | Cl | 41.35 | 41.71 | >50 | >50 | 42.95 | — |
| 127k | <i>Z</i> | H | CF ₃ | H | H | OCH ₂ O | H | 20.09 | 18.90 | 26.0 | >50 | 16.97 | — |
| 127l | <i>E</i> | H | H | F | H | H | H | >50 | 15.13 | >50 | 0.12 | 38.45 | — |
| Paclitaxel | — | — | — | — | — | — | — | 2.29 | 3.99 | 2.56 | 3.87 | 2.32 | 41.7 |
| Camptothecin | — | — | — | — | — | — | — | 6.13 | — | 5.77 | 14.76 | 4.96 | — |
| Chloroquine | — | — | — | — | — | — | — | 29.96 | — | 36.53 | 19.86 | 63.08 | — |
| DMSO | — | — | — | — | — | — | — | — | — | — | — | — | 16.9 |

inhibitory activity. The effect of acrylo phenylacetic acids **139a–c** on the position of the acid group was investigated. The HDAC inhibitory activity of positional isomers **139a–c** was comparable to compounds **131d**, **131p**, **131h**, and **131q**. Encouragingly, compound **139a** with an OCH₃ group in the 4'-position on the phenyl ring was 62-times more potent than compound **131p**. Alternatively, compound **139p** was 38-times less potent than **131a**. The carbonyl group of the amide bond in **131r** reduced to the corresponding amine derivative **135** to produce a secondary amine that is more hydrophilic in nature. Compound **132a** showed 8-times greater HDAC inhibitory activity compared to compound **131d**, while compound **132b** showed 10-times decrease in HDAC inhibitory activity compared to **131q**. Also, the anti-proliferative activity of some compounds was investigated. Among the synthesized compounds, **132a** showed the highest cytotoxicity activity against the NCI-H460, HCT-116, and U-251 cell lines. In addition, compound **131s** with an isopropyl moiety exhibited lower activity than **131d** having cyclopropyl moiety against the tested cell lines. In addition, moving the F atom from the 2'- to 3'-position on the phenyl ring reduced the cytotoxicity against all the tested cell lines (*e.g.*, **131t** and **131n**). Furthermore, the aliphatic groups improved the cytotoxicity compared to aromatic groups (**131u** vs. **131k** and **132c** vs. **132b**) against the tested cell lines. Also, increasing the number of F atoms in 4'-position of compound **131n** produced **131v**, which showed the highest cytotoxicity activity against all the tested cell lines. Furthermore, compound **131m** with EWG on the phenyl ring showed higher cytotoxicity activity than **131l** having EDG against the tested cancer cell lines (Table 33).

Duan *et al.*⁷⁵ designed resveratrol derivatives and tested their activity against LSD1. Compounds **143c** and **d** showed the highest activity against LSD1, and they were more potent than resveratrol and tranlycypromine. In addition, replacing the F atom with an OH group in the 3'-position on the phenyl ring decreased the inhibitory activity against LSD1 (*e.g.*, **143e** and **143f**). Moreover, exchanging the phenyl ring with a pyridine ring (**143g** vs. **147**) or indole ring (**143h** vs. **149**) resulted in a significant decrease in activity, demonstrating the importance of the phenyl ring in retaining the activity. Also, increasing the atom size improved the activity (*e.g.*, **143c** and **143i**). According to the comparison of **143h** and **144**, changing benzimidamide to benzimidohydrazide significantly reduced the inhibitory activity. Amidoxime in the 3-position on the phenyl ring was preferential; the amidoxime in the 3-position on the phenyl ring of derivatives such as **143g** showed higher inhibitory activity than the corresponding amidoxime in the 4-position on the phenyl ring-substituted derivatives (**143h**) against LSD1. Treatment with **143c** and **143d** resulted in the remarkable buildup of H3K4me2, the substrate of LSD1, without influencing LSD1 expression (Table 34).

Ismail *et al.*⁷⁶ synthesized stilbene derivatives and evaluated their tyrosinase inhibitory activity. Compound **152a** showed the highest murine tyrosinase inhibitory activity. This compound exhibited 2-times stronger inhibitory activity than resveratrol against murine tyrosinase. Among the *E*-isomers, compounds **152b** and **152c** showed that fluorination of compound **152d** increased its tyrosinase inhibitory activity. The F-substituted compounds compared to the other halo-substituted



Table 33 Synthetic stilbene derivatives

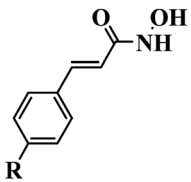
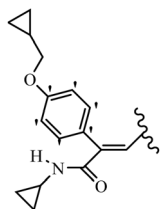
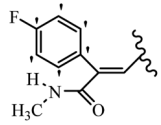
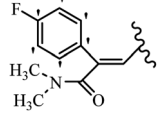
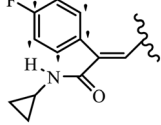
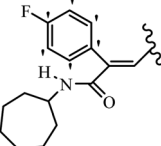
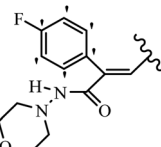
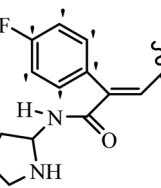
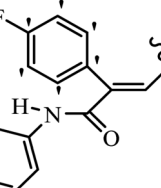
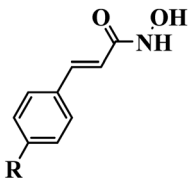
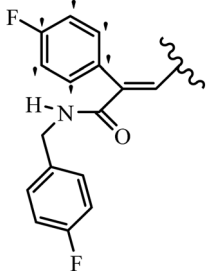
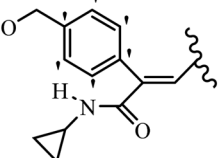
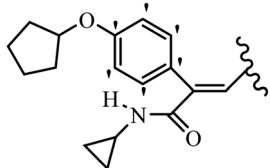
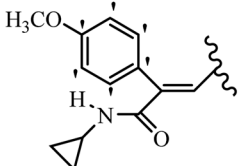
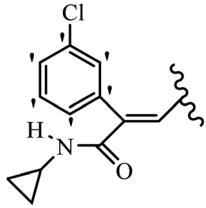
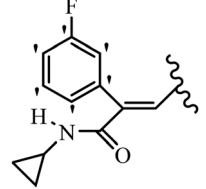
| Compounds | R | IC ₅₀ (nM) | | GI ₅₀ (μM) | |
|--|---|-----------------------|----------|-----------------------|------|
| | | HDAC | NCI-H460 | HCT-116 | U251 |
| |  | | | | |
| (131a-v) (139a,b) (132a-c) (135a-c) | | | | | |
| 131a |  | 3.7 | 0.65 | 0.22 | 0.05 |
| 131b |  | 350 | — | — | — |
| 131c |  | 390 | — | — | — |
| 131d |  | 48 | 1.8 | 1.4 | 0.02 |
| 131e |  | 990 | — | — | — |
| 131f |  | 430 | — | — | — |
| 131g |  | 410 | — | — | — |
| 131h |  | 200 | — | — | — |



Table 33 (Contd.)

| Compounds | R | IC ₅₀ (nM) | | GI ₅₀ (μM) | |
|-----------|--|-----------------------|----------|-----------------------|------|
| | | HDAC | NCI-H460 | HCT-116 | U251 |
| |  (131a-v) (139a,b) (132a-c) (135a-c) | | | | |
| 131i |  | 190 | — | — | — |
| 131j |  | 39 | 2.5 | 2 | 2 |
| 131k |  | 18 | 0.75 | 1 | 1 |
| 131l |  | 68 | 8 | 3 | 1.8 |
| 131m |  | 30 | 0.5 | 0.5 | 1 |
| 131n |  | 40 | 10 | 2 | 4.2 |

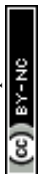
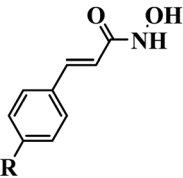
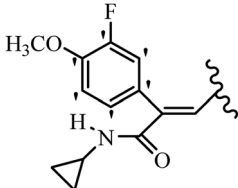
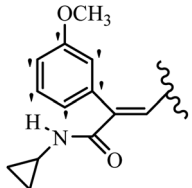
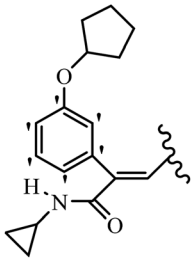
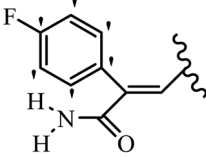
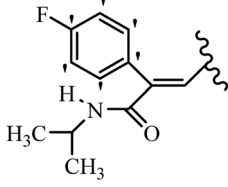
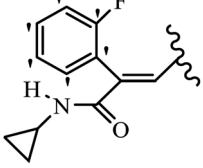


Table 33 (Contd.)

| Compounds | R | IC ₅₀ (nM) | | GI ₅₀ (μM) | |
|-----------|---|-----------------------|----------|-----------------------|------|
| | | HDAC | NCI-H460 | HCT-116 | U251 |
| |  | | | | |
| | (131a-v) (139a,b) (132a-c) (135a-c) | | | | |
| 131o |  | 15 | 9.1 | 1.1 | 3 |
| 131p |  | 310 | — | — | — |
| 131q |  | 56 | 7 | 6 | 6 |
| 131r |  | 240 | — | — | — |
| 131s |  | 80 | 11 | 3 | 10.5 |
| 131t |  | 90 | 13 | 6 | 7 |

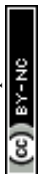
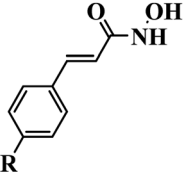


Table 33 (Contd.)

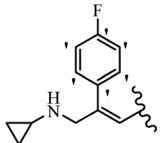
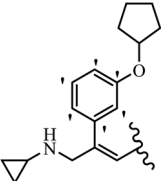
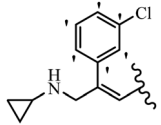
| Compounds | R | IC ₅₀ (nM) | | GI ₅₀ (μM) | |
|-----------|---|-----------------------|----------|-----------------------|------|
| | | HDAC | NCI-H460 | HCT-116 | U251 |
| | (131a-v) (139a,b) (132a-c) (135a-c) | | | | |
| 131u | | 34 | 0.4 | 0.5 | 0.8 |
| 131v | | 30 | 8 | 1.8 | 4 |
| 135a | | 44 | 0.03 | 3.5 | 1.6 |
| 139a | | 5 | 4 | 1 | 2.8 |
| 139b | | 140 | — | — | — |



Table 33 (Contd.)



(131a-v) (139a,b) (132a-c) (135a-c)

| Compounds | R | IC ₅₀ (nM) | | GI ₅₀ (μM) | |
|-----------|--|-----------------------|----------|-----------------------|------|
| | | HDAC | NCI-H460 | HCT-116 | U251 |
| 132a |  | 6 | 0.3 | 0.02 | 0.3 |
| 132b |  | 600 | >100 | >100 | >100 |
| 132c |  | 60 | 0.2 | 0.3 | 0.2 |

compounds in the 4'-position on the phenyl ring and unsubstituted compounds showed no improvement with an increase in molecular weight (F; **152b** < Br; **152e** < Cl; **152f** < **152d**, H). This implies that the effect of fluorination on the activity of stilbene derivatives cannot be attributed to its effect on lipophilicity but rather to the increase in favorable and specific dipolar interactions. The IC₅₀ values of stilbenes substituted with NO₂, CN, CO₂CH₃, OH, and OCH₃ groups supported this hypothesis (**152g**, **152h**, **152i**, **152j**, and **152k**, respectively). Compounds **152k** and **152l** carrying one and four methoxy groups, respectively, reduced the inhibitory activity. Among the Z-isomers, compounds **152m**, **152n**, **152o**, and **152p** exhibited no activity compared to the inhibitory activity of stilbenes. It was observed that the introduction of methyl acetate on the linker carbon in **152p** compared to **152o** with a carboxylic acid group in the same position revealed no notable activity on their inhibition potential. The activity studies for compound **152q** indicated that the pyridine ring decreased the inhibitory activity to an excessive range (Table 35).

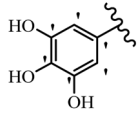
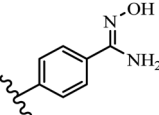
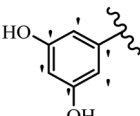
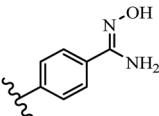
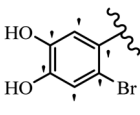
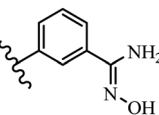
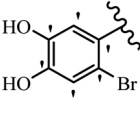
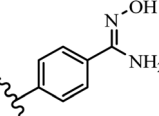
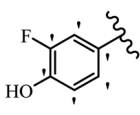
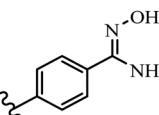
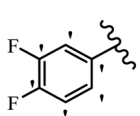
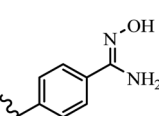
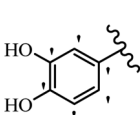
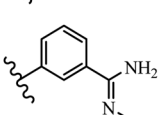
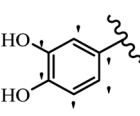
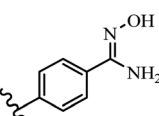
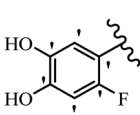
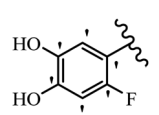
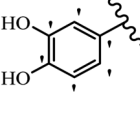
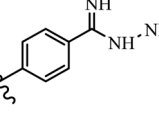
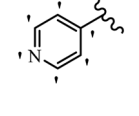
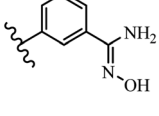
Katherine *et al.*⁷⁷ synthesized stilbene analogues and evaluated their cytotoxicity activity. Compound **185a** showed the highest activity among the synthesized compounds, which was stronger than that of novobiocin against the MCF-7, SK-Br-3, and HCT-116 cell lines. Also, replacing the cyclopropyl linker in compound **182** with a double bond in **181** decreased the

activity. The triazole moiety was replaced by a biaryl amide, which resulted in a significant increase in anti-proliferative activity against all the tested cell lines (**185b** vs. **185c**). When *N*-methyl-piperidine was replaced with 3-(dimethylamino)propane, the activity decreased as in **185d**, while the activity of **185c** was nearly identical to **185e** against the MCF-7, SKBr3 and HCT-116 cell lines. Interestingly, when *Z*-2-(dimethylamino)ethane was added to the stilbene scaffold, both triazole-containing compounds (**185g** and **185f**) showed improved anti-proliferative activity against all the cell lines. Because **185b** is remarkably less active than the standard, it is clear that the improvement in anti-proliferative activity is due to the triazole moiety replacing the biaryl amide side chain (Table 36).

Duan *et al.*⁷⁸ designed stilbene derivatives as LSD1 inhibitors and evaluated their cytotoxicity. Among the synthesized compounds, **190a** and **193a** exhibited the highest activity, and they were more active than ORY-1001. Also, the replacement of the pyridine ring in **190b** with a pyrimidine ring in **190c** intensely reduced the anti-LSD1 activity. In addition, replacing the F in the 3'-position on the pyridine ring of compound **190d** with OH in the same position of **190e** enhanced the activity. Compounds **190f** bearing amine in the 3-position on the phenyl ring showed reduced anti-LSD1 activity comparable to that of **190g** having amidoxime in the same position. However, OH substitution (**190h**, **190i**, and **193b**) led to a dramatic reduction



Table 34 Structures of resveratrol derivatives

| Compound | Ar ₁ | Ar ₂ | IC ₅₀ (μM) | | |
|----------|---|---|-----------------------|---------|-----------|
| | | | LSD1 | H3K4me2 | CD86 mRNA |
| 143a |  |  | — | — | — |
| 143b |  |  | — | — | — |
| 143c |  |  | 0.121 | 6 | 7.70 |
| 143d |  |  | 0.123 | 5.70 | 9 |
| 143e |  |  | 0.492 | — | — |
| 143f |  |  | — | — | — |
| 143g |  |  | 0.333 | — | — |
| 143h |  |  | 0.739 | — | — |
| 143i |  |  | 0.192 | — | — |
| 144 |  |  | — | — | — |
| 147 |  |  | 3.61 | — | — |

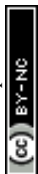
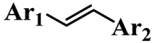
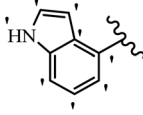
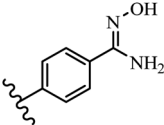


Table 34 (Contd.)

| | |  | | | | |
|-----------------|---|---|-----------------------|---------|-----------|--|
| | | (143a-i, 144, 147, 149) | | | | |
| Compound | Ar ₁ | Ar ₂ | IC ₅₀ (μM) | | | |
| | | | LSD1 | H3K4me2 | CD86 mRNA | |
| 149 |  |  | — | — | — | |
| Resveratrol | — | — | 10.20 | — | — | |
| Tranlycypromine | — | — | 26.31 | — | — | |

activity. Introducing diverse substituents on the pyridine ring (e.g., **190e**) usually resulted in significantly lower activity compared to no substitution in **190a**. This indicates that substituents at this position are unfavorable. The amidoxime or amino moiety placed in the 3-position on the phenyl ring displayed the highest activity. For example, compounds **190a**, **190f** and **193c** were more potent against LSD1 than the corresponding 4-position-substituted derivatives (**190b** and **193d**). The compounds bearing an OCH₃ group in the 2'-position of the arylbenzene moiety (**190j** and **190k**) showed no activity against LSD1 compared with compounds **190a** and **190f**. It seems that the presence of hydrophilic and small-size groups improved the

activity compared to lipophilic and bulk groups, demonstrating the importance of the OH group in maintaining their activities. The synthesized compounds **190a**, **190l**, **193a**, and **193c** with the most potent LSD-inhibitory activity were assessed for their anti-proliferative activities against three MOLM-13, THP-1 and MV-4-11 cell lines. Compound **193a** displayed the best anti-proliferative activity against MOLM-13 and THP-1. Compound **190l** showed fairly higher anti-proliferative activity against MV-4-11, which was more potent than compound **193a** (Table 37).

Singh *et al.*⁴⁸ reported the cytotoxicity of resveratrol structural analogues. The compounds showed no cytotoxicity activity against L929. All the compounds showed weaker activity than

Table 35 Chemical structures of *E/Z*-stilbene derivatives

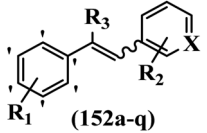
| | |  | | | | |
|-------------|------------|---|----------------------|---------------------------|--------------------|-----------------------|
| | | (152a-q) | | | | |
| Compound | <i>E/Z</i> | X | R ₁ | R ₂ | R ₃ | IC ₅₀ (μM) |
| 152a | <i>Z</i> | CH | — | OH | — | 5.06 |
| 152b | <i>E</i> | — | 4-F | H | — | 79.44 |
| 152c | <i>E</i> | — | 3,5-diF | H | — | 56.16 |
| 152d | <i>E</i> | — | H | H | — | >500 |
| 152e | <i>E</i> | — | 4-Br | H | — | 276.56 |
| 152f | <i>E</i> | — | 4-Cl | H | — | 319.75 |
| 152g | <i>E</i> | — | 4-NO ₂ | H | — | 360.70 |
| 152h | <i>E</i> | — | 4-CN | H | — | 360.70 |
| 152i | <i>E</i> | — | 4-OCOCH ₃ | H | — | >500 |
| 152j | <i>E</i> | — | 4-OH | H | — | 17.42 |
| 152k | <i>E</i> | — | 4-OCH ₃ | H | — | 432.97 |
| 152l | <i>E</i> | — | 4-OCH ₃ | 3,4,5-OCH ₃ | — | 393.99 |
| 152m | <i>Z</i> | — | 4-OCH ₃ | 3,4-OCH ₃ | COOH | — |
| 152n | <i>Z</i> | — | 4-OCH ₃ | 4-OCOCH ₃ | COOH | — |
| 152o | <i>Z</i> | — | 4-OCH ₃ | 3-OCH ₃ , 4-OH | COOH | — |
| 152p | <i>Z</i> | — | 4-OCH ₃ | 3-OCH ₃ , 4-OH | COOCH ₃ | >500 |
| 152q | <i>Z</i> | N | — | H | — | 270.22 |
| Resveratrol | — | — | — | — | — | 10.78 |



Table 36 Structures of stilbene analogues

H_3C $\text{O}-\text{R}-\text{NH}$ OCH_3 OCH_3 R_4O H R_2
(181, 182) **(185a-f)**

| Compound | R | R ₂ | R ₄ | IC ₅₀ (μM) | | |
|------------|---|----------------|----------------|-----------------------|---------|---------|
| | | | | MCF-7 | SK-Br-3 | HCT-116 |
| 181 | | — | — | 0.814 | 0.894 | 0.801 |
| 182 | | — | — | 2.64 | 1.31 | 2.90 |
| 185a | — | | | 0.092 | 0.099 | 0.186 |
| 185b | — | | | 5.86 | 9.68 | 5.51 |
| 185c | — | | | 0.325 | 0.382 | 0.350 |
| 185d | — | | | 0.494 | 0.184 | 0.740 |
| 185e | — | | | 0.326 | 0.231 | 0.301 |
| 185f | — | | | 0.150 | 0.141 | 0.179 |
| 185g | — | | | 0.234 | 0.183 | 0.350 |
| Novobiocin | — | — | — | 1.3 | 0.68 | 3.68 |

resveratrol. Compound **194a** exhibited the highest activity against INT407. In addition, the presence of Br on the phenyl ring in **194a** enhanced the activity compared to no substitution in **194b**. According to the results, the compounds with hydrophilic groups on the phenyl rings had a positive effect on cytotoxicity activity (**194c** and **194d**) (Table 38).

Iqbal *et al.*⁷⁹ synthesized *E*-stilbene hydrazides and tested their cytotoxicity activity. Analogue **199a** showed the best cytotoxicity activity among the synthesized analogues. It was more potent than doxorubicin against MCF-7. Also, **199b** having a Cl

atom in the 4-position exhibited stronger cytotoxicity activity than **199c** bearing an OH group in same position. Moreover, changing its position on the phenyl ring did not change the cytotoxicity activity (**199d** with OH group in 2-position *vs.* **199c**). Likewise, the size of the atom on the phenyl ring did not change the activity (*e.g.*, **199e** and **199f** having a Cl atom and I atom in the 2-position, respectively). All the compounds were more potent than the negative control. Some compounds were stronger than doxorubicin. Analogue **199c** showed higher apoptosis activity than doxorubicin and other compounds.



Table 37 Synthetic structures of stilbene derivatives

| Compound | X | R ₁ | R ₂ | R ₃ | R ₄ | IC ₅₀ (μM) | | | |
|-------------|---|------------------|----------------|----------------|----------------|-----------------------|---------|-------|---------|
| | | | | | | LSD1 | MOLM-13 | THP-1 | MV-4-11 |
| 190a | — | OH | H | H | | 0.301 | 12.51 | 10.51 | 10.94 |
| 190b | — | OH | H | H | | 3.57 | — | — | — |
| 190c | N | OH | H | H | | 9.55 | — | — | — |
| 190d | — | OH | F | H | | — | — | — | — |
| 190e | — | OH | OH | H | | 1.47 | — | — | — |
| 190f | N | OH | H | H | | 0.859 | — | — | — |
| 190g | N | OH | H | H | | 1.29 | — | — | — |
| 190h | — | OH | H | H | | 4.24 | — | — | — |
| 190i | N | OH | H | H | | — | — | — | — |
| 190j | — | OCH ₃ | H | H | | — | — | — | — |
| 190k | N | OCH ₃ | H | H | | — | — | — | — |
| 190l | — | OH | H | H | | 0.72 | 22.59 | 7.89 | 4.71 |

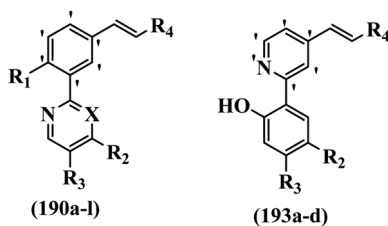
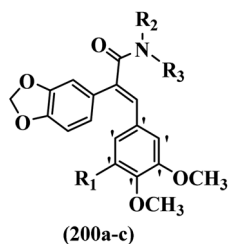


Table 40 Structures of stilbene derivatives containing a 1,3-benzodioxole moiety



| Compound | R ₁ | R ₂ | R ₃ | IC ₅₀ (μg mL ⁻¹) | | |
|----------|------------------|----------------|----------------|---|-------|---------|
| | | | | HepG-2 | A875 | MARC145 |
| 200a | H | H | | 16.53 | >40 | >40 |
| 200b | H | H | | 22.57 | >40 | >40 |
| 200c | OCH ₃ | H | | 25.65 | >40 | >40 |
| 5-FU | — | — | — | 9.41 | 10.66 | 10.09 |

group in the 3'-position on the phenyl ring in **200c** showed less activity compared to **200a** with no substitution in the phenyl ring. In addition, large-size and lipophilic groups had a positive effect on activity (**200a** and **200b**, respectively) (Table 40).

Wong *et al.*⁸⁰ synthesized stilbene long-chain fatty acid conjugates and assessed their cytotoxicity. Among the compounds, **203a** and **206a** exhibited the highest activity and they were stronger than colchicine against the KB-3-1b, NCI-H460c, and HEK-293 cell lines. All the compounds showed weaker cytotoxicity activity compared to colchicine against MCF-7. *E*-Stilbenes showed lower cytotoxicity than the *Z*-isomer (**206b** vs. **206c**) against all four cell lines. Moreover, stilbene **206d** showed considerably decreased cytotoxicity compared to compound **206e** against the HEK-293 cell line. Compound **206f** showed higher activity than **206g** on all the tested cell lines. Compounds **206d** and **206h** exhibited weak activity against all the tested cell lines (Table 41).

Das *et al.*⁸¹ synthesized and tested stilbene-linked 1,2,3-triazoles against six cell lines. All the synthesized compounds showed lower cytotoxicity activity than docetaxel and staurosporine against the HCT-116, Capan-1, K-562, DND-41, Z-138, and NCI-H460 cell lines. Compounds **213a** and **b** exhibited the highest activity among them against the HCT-116, Capan-1, and NCI-H460 cell lines. Furthermore, the replacement of the OCH₃ group in **213c** with a Cl atom in **213d** resulted in lower activity against NCI-H460, HCT-116, and Capan-1. It seems that hydrophilic groups displayed stronger activity than lipophilic groups. In addition, no substitution in **213e** exhibited better activity compared to substitution on the phenyl ring in **213f** against the Capan-1, NCI-H460, DND-41, and K-562 cell lines. Also, the presence of EDG compared to EWG on the phenyl or benzyl ring had a positive effect on cytotoxicity against Capan-1, HCT-116, and NCI-H460 (*e.g.*, **213g** vs. **213h**) (Table 42).

4. Liver enzyme inhibitors

Kim *et al.*⁸² synthesized *E*-stilbene analogues and evaluated their inhibitory activity on human CYP1A1, CYP1A2, and CYP1B1. Compound **216a** displayed the highest inhibitory activity on CYP1A1, CYP1A2, and CYP1B1. This compound was also more potent than oxyresveratrol. Replacing the OH groups of oxyresveratrol with OCH₃ groups in **216b** improved the inhibitory activity and produced deep variations in selectivity against CYP1A1, CYP1A2, and CYP1B1. A change in the position of the OCH₃ groups on the phenyl ring of compounds **216c** (in 3', 4'- and 5'-positions), **216d** (in 3'- and 5'-positions), **216e** (in 3'- and 4'-positions), and **216f** (in 4'-position) resulted in a decrease in potency and selectivity. These findings suggested that the precise location of the OCH₃ groups is a critical feature for selectivity. When the ethylene linker of compound **216b** was replaced with an amide or an imine linker (**220** and **218**), there was no remarkable inhibitory activity on CYPs. In another modification, the phenyl ring was replaced with 4-pyridyl and 3-furanyl rings (**216g** and **216h**), which reduced the activity compared to other compounds. However, **216a** with 2-thiophenyl exhibited the highest inhibitory activity on CYPs, while none of them was as selective as **216b**. Therefore, replacing the OCH₃ group in the 2'-position on the phenyl ring of **216b** with an OH or F in compounds **216i** and **216j** showed less inhibitory activity on CYP1A1, CYP1A2, and CYP1B1, respectively. Also, the presence of lipophilic groups and EWG in **216j** showed higher inhibitory activity than hydrophilic groups and EDG in **216i** (Table 43).

Das *et al.*⁸³ synthesized pinacolyl boronate-substituted stilbenes and tested them as lipogenic inhibitors. Among the synthesized compounds, **227a** showed the highest lipogenic inhibitory activity, which was greater than that of DMSO. Compound **227b** exhibited the lowest activity among the compounds, which was equal to that of DMSO. Also, replacing the OCH₃ group in the 4'-position on the phenyl ring with an OH group in the same position decreased the activity (**227a** vs. **227b**). It seems that the hydrophilic group had a positive effect on activity. In addition, the presence of an OH group in the 6'-position on the phenyl ring in **227c** displayed almost equal activity compared to **227d** (Table 44).

Mikstacka *et al.*²³ synthesized *E*-resveratrol analogues and evaluated their inhibitory activity on some CYPs. Among the synthesized compounds, **226a** and **226b** showed the highest inhibitory activity against CYPs. Also, shifting the OCH₃ group in the 4'- to 5'-position on the phenyl ring reduced the activity (**226c** vs. **226d**) on CYP1A1 and CYP1A2. In contrast, **226d** had better inhibitory activity than **226c** on CYP1B1. Compounds having substituents in the 2'- and 4'-positions showed higher affinity to the CYP1A2 active site (**226c**). However, based on the results, CYP1A2 is the most sensitive to changes in the design of methoxy substituents. Compound **226e** with OCH₃ groups in the 3', 4', and 5'-positions on the phenyl ring did not reduce the affinity of these three OCH₃ groups on the phenyl ring to CYP1A2, but it significantly increased the inhibitory potency against CYP1A1 and CYP1B1. In addition, increasing the



Table 41 Structures of stilbene long-chain fatty acid conjugates

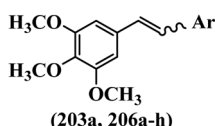
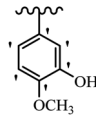
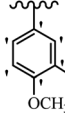
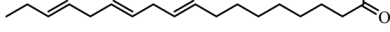
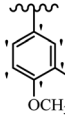
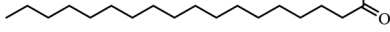
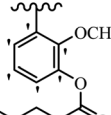

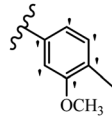
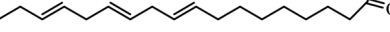
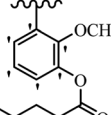

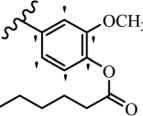

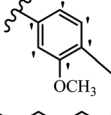

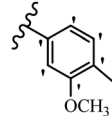
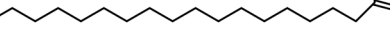
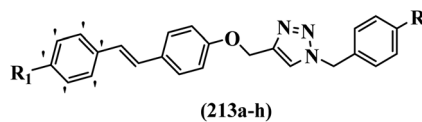
| Compound | <i>E/Z</i> | Ar | IC ₅₀ (μM) | | | |
|------------|------------|--|-----------------------|----------|---------|-------|
| | | | KB-3-1 | NCI-H460 | HEK-293 | MCF-7 |
| | |  (203a, 206a-h) | | | | |
| 203a | <i>Z</i> |  | 0.01 | 0.01 | 0.01 | 0.09 |
| 206a | <i>Z</i> |   | 0.03 | 0.01 | 0.023 | >10 |
| 206b | <i>Z</i> |   | 0.03 | 0.03 | 0.03 | 0.24 |
| 206c | <i>E</i> |   | >10 | >10 | 2.90 | >10 |
| 206d | <i>E</i> |   | >100 | >100 | >100 | >100 |
| 206e | <i>E</i> |   | 2.40 | >10 | 2.40 | >10 |
| 206f | <i>Z</i> |   | 3.10 | >10 | 3.90 | 7.70 |
| 206g | <i>Z</i> |   | >100 | >100 | >100 | >100 |
| 206h | <i>E</i> |   | >100 | >100 | >100 | >100 |
| Colchicine | — | — | 0.02 | 0.06 | 0.02 | 0.06 |



Table 42 Chemical structures of stilbene-linked 1,2,3-triazoles



| Compounds | R ₁ | R | IC ₅₀ (μM) | | | | | |
|---------------|------------------|-----------------|-----------------------|---------|----------|--------|--------|--------|
| | | | Capan-1 | HCT-116 | NCI-H460 | DND-41 | K-562 | Z-138 |
| 213a | F | NO ₂ | 40.2 | 12.2 | 11.6 | >100 | >100 | >100 |
| 213b | F | H | 30.7 | 46.7 | 31.7 | >100 | >100 | >100 |
| 213c | OCH ₃ | H | 55.3 | 13.5 | 35.1 | >100 | >100 | >100 |
| 213d | Cl | H | 96.4 | 36.1 | >100 | >100 | 19.3 | >100 |
| 213e | H | H | 46.7 | 29.1 | 34.3 | 61.4 | 39.9 | >100 |
| 213f | H | NO ₂ | >100 | 26.1 | 78.5 | 82.1 | >100 | >100 |
| 213g | CH ₃ | CH ₃ | 52.4 | 87.4 | 60.8 | >100 | >100 | >100 |
| 213h | F | CH ₃ | 73.4 | >100 | >100 | >100 | >100 | >100 |
| Docetaxel | — | — | 0.0063 | 0.0008 | 0.0001 | 0.0019 | 0.0034 | 0.0019 |
| Staurosporine | — | — | 0.0046 | 0.0003 | 0.0032 | 0.0064 | 0.0298 | 0.0003 |

number of OCH₃ groups on the phenyl ring improved the inhibitory activity (226d vs. 226f). The results showed that the EWG and lipophilic groups had better activity compared to EDG and hydrophilic groups (Table 45).

Mikstacka *et al.*²⁴ designed *E*-stilbene derivatives and evaluated their inhibitory activity on CYP450. The synthesis method in this study was described in a previous report.¹⁸ Compounds 227a and b showed the highest activity on CYP1A1, CYP1A2, and CYP1B1 among the synthesized compounds. All the compounds strongly inhibited CYP1A1 activity. Compound 227b was a selective inhibitor of CYP1B1, showing a 90-times higher selectivity for CYP1B1 over CYP1A1 and 830-times higher selectivity for CYP1B1 over CYP1A2. In addition, moving the OCH₃ group in the 3'- to the 5'-position on the phenyl ring enhanced the CYP1A1 inhibition activity (227c vs. 227d). Adding an OCH₃ group in the 3'-position on the phenyl ring in 227b produced 227e, which exhibited lower activity against CYP1A1, CYP1A2, and CYP1B1. Moreover, attaching an OCH₃ group in the 4'-position on the phenyl ring in 227f showed stronger activity than 227a against CYP1A2. In contrast, 227a and 227f showed almost equal activity for CYP1A1 and CYP1B1. Also, increasing the number OCH₃ groups on the phenyl ring had a negative effect on activity (*e.g.*, 227e and 227g). In addition, changing the position of the OCH₃ group on the phenyl ring in 227f, 227d, and 227e improved the inhibitory activity against CYP1A1. Therefore, according to the results, the activity followed the order of 6' > 5' > 4' (Table 46).

Wierzchowski *et al.*⁸⁴ tested *E*-methylthio stilbene derivatives as CYP450 inhibitors. The synthesis method of this study is mentioned in the previous study.²³ All the tested compounds inhibited the CYP1A1 and CYP1B1 activities, but only moderately inhibited CYP1A2. Compounds 228a–c showed the highest activity and they were stronger than the standard α -naphthoflavone on CYPs. Also, the addition of an OCH₃ group in the 3'-position on the phenyl ring of 228c enhanced the inhibitory activity compared to no substitution in 228d. According to the

results, both hydrophilic and lipophilic groups on both phenyl rings improved the inhibitory activity (Table 47).

5. Anti-Alzheimer's activity

One of the most common neurodegenerative diseases is Alzheimer's disease (AD). It is assessed that there is one new case of dementia every 3 seconds around the world. Fifty million people worldwide were living with dementia in 2018, and this number is rapidly increasing in countries with an aging population.⁸⁵ Although the biology of AD is very complex and not completely determined, some factors such as abnormal A β appearance and buildup, reduction of acetylcholine (ACh), tau hyperphosphorylation, dyshomeostasis of biometals, and oxidative stress have been determined to play significant roles in the pathophysiology of AD.⁸⁶ In this case, resveratrol has health functional properties in neuronal degenerative pathologies such as AD.⁸⁷ Trans-resveratrol and *trans*-piceatannol exhibited a good binding mode *in silico* against AChE. Scirpusin A and cassigarol E displayed inhibitory potential against butyrylcholinesterase (BChE) and AChE compared to tacrine and donepezil.⁸⁸

Lu *et al.*⁸⁹ synthesized resveratrol derivatives and tested their A β -aggregation inhibitory activity. Compound 233a showed the highest inhibitory effect on A β fibrillization among the synthesized compounds. This compound exhibited stronger activity than curcumin and equal activity to resveratrol. Likewise, changing the position of the dimethylamino group in 233b from the 2'- to 4'-position on the phenyl ring in compound 233c resulted in increased activity. Among the four substituted groups (dimethylamino groups; 233a, pyridyl; 233d, Br; 233e and alkyl; 233f), the dimethylamino group showed the best result. In addition, the inhibitory activity of 237g was not significantly changed when the dimethylamino group was replaced with one- or two-substituted amino groups. Also, replacing the OCH₃ groups in the 3- and 5-positions on the



Table 43 Structures of *E*-stilbene analogues

| Compound | Ar | IC ₅₀ (nM) | | |
|----------|----|-----------------------|---------|--------|
| | | 1A1 | 1A2 | 1B1 |
| | | | | |
| | | (216a-j, 218, 220) | | |
| 216a | | 61 | 11 | 2 |
| 216b | | 300 | 3100 | 6 |
| 216c | | 140 | 930 | 3200 |
| 216d | | 920 | 198 000 | 17 600 |
| 216e | | 750 | 570 000 | 3000 |
| 216f | | 830 | 6200 | 790 |
| 216g | | 1100 | 290 | 460 |
| 216h | | 6600 | 740 | 2100 |
| 216i | | 980 | 31 100 | 390 |
| 216j | | 610 | 5800 | 97 |

Table 43 (Contd.)

| Compound | Ar | IC ₅₀ (nM) | | |
|----------------|----|-----------------------|----------------------|--------|
| | | 1A1 | 1A2 | 1B1 |
| | | | | |
| | | (216a-j, 218, 220) | | |
| 218 | | 1500 | 64 000 | 670 |
| 220 | | 300 | >2 × 10 ⁶ | 4900 |
| Oxyresveratrol | — | 15 000 | 150 000 | 34 000 |

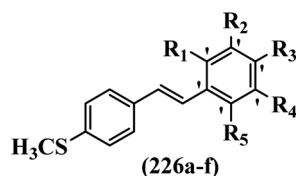
phenyl rings of **232a** compared to **233c** with an OH group in the same position reduced the inhibitory activity. These findings suggested that hydrogen bonds play an important role in the interaction of polyphenols and proteins. Compound **233h**, whose carbon-carbon double bond is reduced compared to the structure of compound **233c**, demonstrated lower activity (Table 48).

Andhare *et al.*⁹⁰ designed *E*-distyrylbenzenes and tested their activity against Alzheimer's disease. Compound **236a** showed the highest activity against A β -aggregation. Also, changing the position of the nitrostyrylbenzene moiety from the 3-position in **236b** to the 4-position on the phenyl ring in **236c** enhanced the activity. Likewise, the presence of substitution on the phenyl ring between two phenyl stilbene rings decreased the activity (**239a** and **239b**). In addition, replacing the biphenyl ring in **239c** with a phenyl ring in **239d** reduced the activity. Moreover, compound **236d** exhibited the highest inhibitory activity against

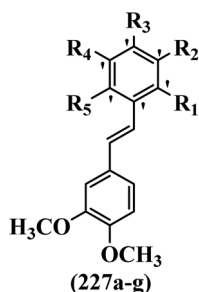
Table 44 Structure of analogues of pinacolyl boronate-substituted stilbenes

| Compound | R ₁ | R ₂ | R ₃ | R ₄ | FAS relative mRNA level |
|----------|----------------|------------------|----------------|----------------|-------------------------|
| | | | | | |
| | | | | | |
| | (223a-d) | | | | |
| 223a | H | OH | H | H | 0.39 |
| 223b | H | OCH ₃ | H | H | 1.0 |
| 223c | Cl | H | Cl | OH | 0.57 |
| 223d | Cl | H | Cl | H | 0.58 |
| DMSO | — | — | — | — | 1.0 |



Table 45 Synthetic structures of *E*-resveratrol analogues

| Compound | R ₁ | R ₂ | R ₃ | R ₄ | R ₅ | IC ₅₀ (μM) | | |
|----------|------------------|------------------|------------------|------------------|------------------|-----------------------|--------|--------|
| | | | | | | CYP1A1 | CYP1A2 | CYP1B1 |
| 226a | OCH ₃ | H | OCH ₃ | H | OCH ₃ | 0.4 | 6.5 | 0.5 |
| 226b | Cl | H | H | H | H | 1.0 | 14.5 | 0.3 |
| 226c | OCH ₃ | H | OCH ₃ | H | H | 2.4 | 8.1 | 2.0 |
| 226d | OCH ₃ | H | H | OCH ₃ | H | 3.8 | 39.5 | 1.1 |
| 226e | H | OCH ₃ | OCH ₃ | OCH ₃ | H | 3.6 | 7.0 | 2.6 |
| 226f | OCH ₃ | H | OCH ₃ | OCH ₃ | H | 0.8 | 15.0 | 0.9 |

Table 46 Structures of *E*-stilbene derivatives

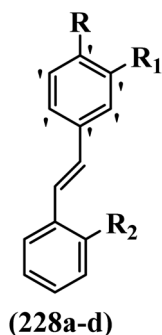
| Compound | R ₁ | R ₂ | R ₃ | R ₄ | R ₅ | IC ₅₀ (μM) | | |
|----------|------------------|------------------|------------------|------------------|------------------|-----------------------|--------|--------|
| | | | | | | CYP1A1 | CYP1A2 | CYP1B1 |
| 227a | OCH ₃ | — | — | — | OCH ₃ | 0.23 | 2.31 | 0.31 |
| 227b | OCH ₃ | — | — | — | — | 0.36 | 3.32 | 0.0040 |
| 227c | OCH ₃ | OCH ₃ | OCH ₃ | — | — | 5.18 | >100 | 4.17 |
| 227d | OCH ₃ | — | OCH ₃ | OCH ₃ | — | 1.78 | >100 | 4.44 |
| 227e | OCH ₃ | OCH ₃ | — | — | — | 0.45 | 16.02 | 0.37 |
| 227f | OCH ₃ | — | OCH ₃ | — | OCH ₃ | 0.27 | >100 | 0.30 |
| 227g | OCH ₃ | — | — | OCH ₃ | — | 0.50 | >100 | 0.62 |

AChE. Compound **236c** showed better activity compared to **236b**. According to the results, the presence of both lipophilic and hydrophilic groups enhanced the activity (**236a**, **236e**, and **236f** and **236d**) against Aβ-aggregation and AChE (Table 49).

Patel *et al.*⁸⁶ designed carbazole-stilbene hybrids and tested their anti-Alzheimer's activity. Among the compounds, **245a** against hAChE and **246a** against EqBuChE showed the highest activity. These compounds were weaker than tacrine and donepezil. They were also stronger than *E*-9-ethyl-3-styryl-9*H*-carbazole against hAChE and EqBuChE. In the first series, comparing the compounds with piperidine rings (**245a**, **245b**, and **245c**), compound **245a** ($n = 4$) showed the best inhibitory activity against AChE, while compounds **245b** ($n = 3$) and **245c** ($n = 2$) exhibited the weakest inhibitory activity. A similar

pattern was seen for the compounds with pyrrolidine rings (**245d**, **245e**, and **245f**). Compound **245b** exhibited the strongest inhibitory activity against BuChE among them. When the pyrrolidinyl ring in **246b** and piperidinyl ring in **246c** were attached directly to provide urea derivatives, the inhibitory effect against both enzymes was reduced, particularly compared to the first series. When amide linkers (*e.g.*, **245d**) were replaced with urea linkers (*e.g.*, **246d**), there was no significant change in inhibitory activities. In the second series, a comparison of the inhibitory potential of compounds **251a**, **251b**, and **251c** with a pyrrolidine ring revealed that compound **246b** ($n = 2$) had the best profile of AChE and BuChE inhibitory activity, whereas compounds **251a** ($n = 1$) and **251c** ($n = 3$) showed slightly lower AChE and BuChE inhibitory activities. All the urea derivatives inhibited ChEs the



Table 47 Chemical structures of *E*-methylthio stilbene derivatives

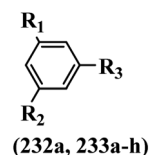
| Compound | R | R ₁ | R ₂ | IC ₅₀ (μM) | | |
|----------|------------------|------------------|------------------|-----------------------|--------|--------|
| | | | | CYP1A1 | CYP1A2 | CYP1B1 |
| 228a | SCH ₃ | H | OCH ₃ | 0.076 | 8.38 | 0.034 |
| 228b | OCH ₃ | OCH ₃ | SCH ₃ | 0.76 | 3.54 | 0.029 |
| 228c | OCH ₃ | OCH ₃ | OCH ₃ | 0.36 | 4.93 | 0.0034 |
| 228d | OCH ₃ | H | OCH ₃ | 0.75 | 4.13 | 0.066 |
| ANF | — | — | — | 0.012 | 0.0038 | 0.0013 |

most, while compounds **252a** and **252b**, in which the heterocyclic amine was directly attached to form urea, inhibited them the least. When the amide linkers in compound **251d** were replaced with urea linkers in compound **252c**, there was no significant change in AChE inhibitory activity, but the BuChE inhibitory activity increased by 2-times. All the thiourea derivatives demonstrated excellent inhibitory activity against ChEs. Among them, compound **252e** ($n = 2$) was conferred with the highest inhibitory activity against AChE and BuChE. Then, the Aβ₁₋₂-aggregation inhibition activity was tested. Compound **252d** showed the highest activity among the compounds, which was better than curcumin. Almost all the compounds showed relatively similar Aβ₁₋₂-aggregation inhibitory activity. According to the results, lipophilic groups improved the activity against AChE, BuChE, and Aβ₁₋₂-aggregation (Table 50).

6. Antioxidant activity

The imbalance in antioxidant reactions caused by the buildup of free radicals in the body and oxidation results in oxidative stress.⁹¹ The highest free radicals in cells, mostly formed by mitochondria, are produced by reactive oxygen species (ROS).⁹² Excess ROS disturb metabolic function, break down cells and tissues, and lead to diverse health problems.⁹³ Antioxidants are a group of compounds that aid in neutralizing and trapping free radicals, and thus they can reduce the harm to the body caused by free radicals.^{94,95} Natural phenolic derivatives are a vital group of antioxidants investigated and widely used in the nutritional and biopharmaceutical fields to inhibit oxidation processes.⁹⁶ Stilbenes, as polyphenolic compounds,⁹⁷ possess interesting antioxidant activity.⁹⁶ The hydroxy group is important for antioxidant activity, which can be due to the stabilization *via* resonance in the double-bond linker.⁹⁸ Resveratrol

Table 48 Structures of resveratrol derivatives



| Compound | R ₂ | R ₂ | R ₃ | Inhibition percent (%) |
|-------------|------------------|------------------|----------------|------------------------|
| | | | | Aβ-aggregation |
| 232a | OCH ₃ | OCH ₃ | | 7.02 |
| 233a | OH | OH | | 71.65 |
| 233b | OH | OH | | 59.40 |
| 233c | OH | OH | | 65.20 |
| 233d | OH | OH | | 13.56 |
| 233e | OH | OH | | 25.23 |
| 233f | OH | OH | | 43.56 |
| 233g | OH | OH | | 65.50 |
| 233h | OH | OH | | 48.54 |
| Resveratrol | — | — | — | 69.73 |
| Curcumin | — | — | — | 52.77 |

exhibited antioxidant activity in tumor initiation, promotion and progression, disturbing its progression by blocking the S and G2 phases of the cell cycle.⁹⁹

Jung *et al.*¹⁵ synthesized *E*-stilbene derivatives and evaluated their antioxidant activity. The synthesis method of this study was mentioned in a previous study.⁴⁴ Most of the compounds showed equal antioxidant activity to resveratrol. Compounds **253a** and **253b** exhibited the highest antioxidant activity among the synthesized compounds. These compounds were also better than resveratrol. Compound **253c** with an *N*-tetrahydrofuran-2-ylmethylaminocarbonyl moiety in the 4'-position on the phenyl



Table 49 Chemical structures of *E*-distyrylbenzenes

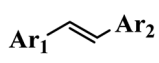
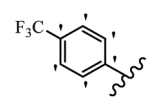
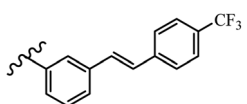
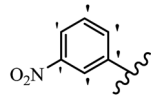
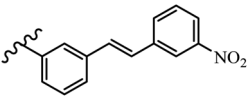
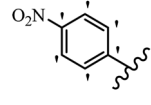
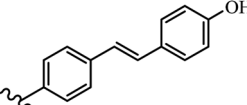
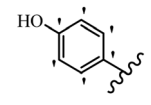
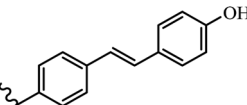
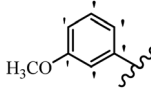
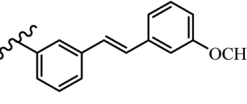
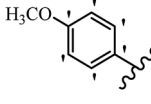
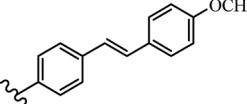
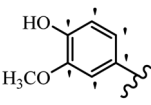
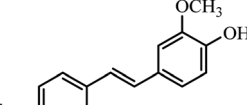
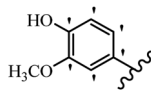
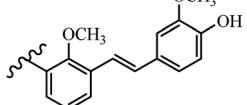
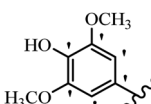
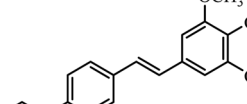
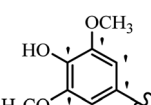
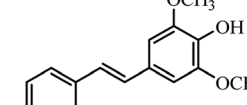
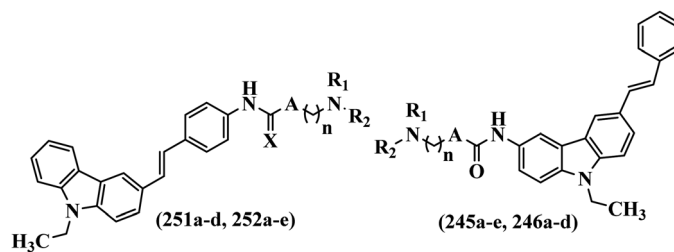
| Compound | Ar_1  Ar_2 | | $\text{A}\beta$ -aggregation (μM) | AChE (μM) |
|----------|---|---|--|------------------------|
| | Ar_1 | Ar_2 | | |
| 236a |  |  | 40 | 100 |
| 236b |  |  | 75 | 180 |
| 236c |  |  | 55 | 610 |
| 236d |  |  | 45 | 70 |
| 236e |  |  | 100 | 55 |
| 236f |  |  | 65 | 80 |
| 239a |  |  | 35 | 40 |
| 239b |  |  | 70 | 40 |
| 239c |  |  | 55 | 80 |
| 239d |  |  | 45 | 80 |



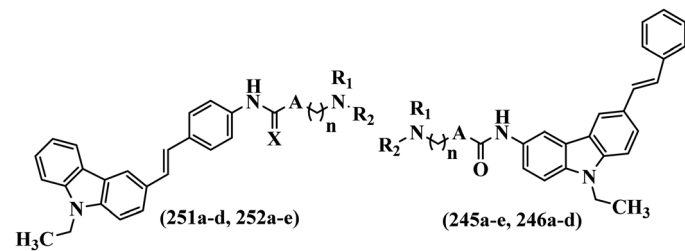
Table 50 Synthetic compounds of carbazole–stilbene derivatives

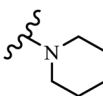
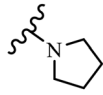
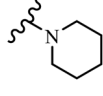
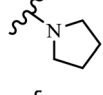
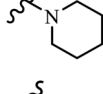
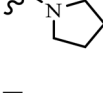


| Compound | n | X | A | NR ₁ R ₂ | IC ₅₀ (μM) | | Inhibition percent (%) |
|----------|---|---|----|--------------------------------|-----------------------|---------|--|
| | | | | | hAChE | EqBuChE | Aβ ₁ -β ₂ -Aggregation |
| 245a | 4 | — | — | | 1.84 | 2.51 | 48.09 |
| 245b | 2 | — | — | | 4.96 | 1.40 | 52.08 |
| 245c | 3 | — | — | | 3.54 | 2.56 | 49.88 |
| 245d | 2 | — | — | | 3.00 | 1.53 | 42.72 |
| 245e | 3 | — | — | | 2.91 | 1.51 | 53.92 |
| 245f | 4 | — | — | | 2.63 | 3.17 | 46.72 |
| 246a | 3 | — | NH | | 3.57 | 1.02 | 54.35 |
| 246b | — | — | — | | 6.63 | 4.48 | 17.58 |
| 246c | — | — | — | | 5.99 | 5.01 | 21.55 |
| 246d | 2 | — | NH | | 2.65 | 1.70 | 52.29 |
| 251a | 1 | O | — | | 2.98 | 2.49 | 51.14 |
| 251b | 2 | O | — | | 2.36 | 1.46 | 54.27 |
| 251c | 3 | O | — | | 4.77 | 4.76 | 53.08 |



Table 50 (Contd.)



| Compound | <i>n</i> | X | A | NR ₁ R ₂ | IC ₅₀ (μM) | | Inhibition percent (%) |
|-----------|----------|---|----|---|-----------------------|---------|--|
| | | | | | hAChE | EqBuChE | Aβ ₁ -β ₂ -Aggregation |
| 251d | 3 | O | — |  | 3.29 | 2.11 | 49.78 |
| 252a | — | O | — |  | 16.22 | 11.65 | 42.84 |
| 252b | — | O | — |  | 12.37 | 8.58 | 44.15 |
| 252c | 2 | O | NH |  | 4.71 | 2.32 | 38.90 |
| 252d | 2 | O | NH |  | 3.13 | 1.20 | 55.79 |
| 252e | 2 | S | NH |  | 2.64 | 1.29 | 51.29 |
| CS-1 | — | — | — | — | >100 | >100 | 27.52 |
| Tacrine | — | — | — | — | 0.056 | 0.008 | — |
| Donepezil | — | — | — | — | 0.023 | 1.87 | — |
| Curcumin | — | — | — | — | — | — | (IC ₅₀ = 20.43 μM) |

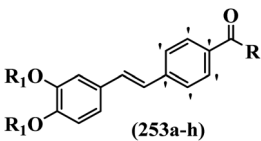
ring showed lower activity compared to **253d** having *N*-furan-2-ylmethylaminocarbonyl in the same position. In addition, the presence of *N*-(3-ethoxycarbonylphenyl)aminocarbonyl of **253e** showed higher antioxidant activity than **253f** with no substitution in the same position. The results showed that acyclic amine moieties displayed higher radical-scavenging activity than the cyclic amine moieties in the 4'-position on the phenyl ring (e.g., **253b**, and **253g**). Also, the presence of an aromatic ring compared to an aliphatic ring reduced the activity (**253f** and **253h**) (Table 51).

Lu *et al.*⁸⁹ investigated the antioxidant activity of resveratrol compounds. Among the compounds, **254a** demonstrated the highest antioxidant activity, which was comparable to that of resveratrol. Furthermore, a secondary amine in the 4-position on the phenyl ring of **254b** and **254c** displayed higher

antioxidant activity than a tertiary amine in **254d** in the same position. The findings indicated that the amine groups in the 4-position on the phenyl ring play a significant role in the antioxidant effect. According to the results, the presence of two propyl chains on the tertiary amine and cyclohexyl ring on the secondary amine resulted in an increase in antioxidant activity (**254e** and **254f**) (Table 52).

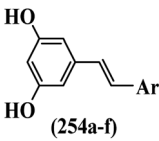
Patel *et al.*⁸⁶ designed carbazole–stilbene hybrids and evaluated their antioxidant activity. Most of the compounds exhibited weak activity. Among them, **255a** showed the highest activity, but weaker activity than ascorbic acid. In addition, replacing the sulfur atom with oxygen increased the antioxidant activity (**255b** vs. **255c**). It seems that increasing the atom size and lipophilic groups improved the antioxidant activity. The other compounds showed almost equal activity (Table 53).



Table 51 Synthetic compounds of *E*-stilbene derivatives


| Compound | R | R ₁ | IC ₅₀ (μM) | Antioxidant activity |
|-------------|---|----------------|-----------------------|----------------------|
| 253a | | H | 47.87 | |
| 253b | | H | 43.59 | |
| 253c | | H | >200 | |
| 253d | | H | 69.0 | |
| 253e | | H | 126.63 | |
| 253f | | H | >200 | |
| 253g | | H | >200 | |
| 253h | | H | 127.93 | |
| Resveratrol | — | — | >200 | |

Table 52 Structures of resveratrol derivatives



| Compound | Ar | ORAC |
|-------------|----|------|
| 254a | | 5.54 |
| 254b | | 5.19 |
| 254c | | 4.33 |
| 254d | | 3.31 |
| 254e | | 2.23 |
| 254f | | 2.25 |
| Resveratrol | — | 5.92 |

molecular structure of a compound by extending a conjugated system within it, from compound **262** to **270a**, resulted in more potent inhibition of PTP1B. However, 3',4'-dihydroxycinnamic acid **272** and its amide analogs, **274a** and **274b**, exhibited no activity. This indicated that the phenyl ring linked by the double bond is essential for PTP1B inhibition. According to the findings, it seemed that the OH groups in the 3'- and 4'-positions on the phenyl ring and EWGs in the 2- and 4-positions on the phenyl ring, such as ester (**262** and **270a**), aldehyde (**264b**), nitro (**276a** and **276b**) and amides (**264a**) of *E*-stilbene analogues enhanced the inhibitory effect against PTP1B. It is important that *E*-isomers (**270a**) are relatively more potent than *Z*-isomers (**271a**), which may be due to their binding appropriateness to the PTP1B active site (Table 54).

Mizuno *et al.*¹⁰⁶ studied pterostilbene analogues for peroxisome proliferator-activated receptor α (PPAR α) activation. The NO₂ group in compounds *E/Z*-**280a** and NH₂ group in *E/Z*-**281a** in the 4-position on the phenyl ring remarkably activated PPAR α . Among the *Z*-isomers, compound **280c** having an OCH₃ group in the 4-position on the phenyl ring had significant activity as a PPAR α agonist (>2-times). The introduction of an ester group (**280b** having COOCH₃ in the 4-position on the phenyl ring) also resulted in an improvement in activity (>2-

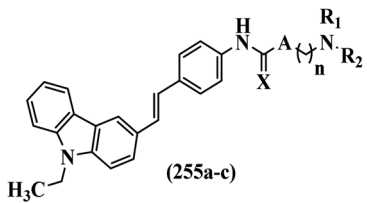
7. Antidiabetic activity

Diabetes mellitus is an endocrine metabolic disorder identified by abnormal levels of glucose in the blood stream. Chronic hyperglycemia can cause severe long-term problems including kidney failure, cardiovascular disease, and nerve damage.¹⁰⁰ In this case, resveratrol and rosewood exhibited anti-diabetic activity.¹⁰¹ Also, stilbenes showed potent inhibitory activity against α -glucosidase.^{102,103} In mice nourished by a high-fat diet, they improved the insulin resistance. Resveratrol is also known to regularize hyperglycemia, and significantly improve hyperinsulinemia in diet-induced obese and diabetic mice.¹⁰⁴

Jung *et al.*¹⁰⁵ synthesized stilbene derivatives and tested their inhibitory activity against protein tyrosine phosphatase 1B (PTP1B). Compound **270a** showed the highest inhibitory activity against PTP1B. It was more potent than molybdate and RK-682. Also, replacing alcohol and aldehyde in **263a** and **264a** instead of methyl ester in **262** reduced the activity. Modifying the



Table 53 Structures of carbazole–stilbene hybrids



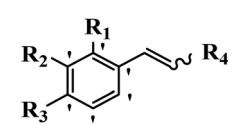
| Compound | <i>n</i> | X | A | NR ₁ R ₂ | Inhibition percent (%) | |
|---------------|----------|---|----|--------------------------------|------------------------|-------|
| | | | | | DPPH | PTP1B |
| 255a | 2 | S | NH | | 72.36 | |
| 255b | 3 | O | NH | | 45.95 | |
| 255c | 3 | S | NH | | 70.36 | |
| Ascorbic acid | — | — | — | — | 98.25 | |

times). To study the role of the vinyl double bond of pterostilbene in the activation of PPAR α , saturated compound **283a** was evaluated. Saturation of the double bond changed the conformation of the molecule, resulting in the loss of activity. The most active compound in this series was phosphate derivative **283a**. This displayed that the addition of an acidic group resulted in greater activity. It is possible that **283a** with dihydrogen phosphate in the 4-position on the phenyl ring acts as a prodrug, resulting in the observed increase in activity. In general, compounds *E*-**280b** and *E/Z*-**280c** bearing an OCH₃ group in the 4-position on the phenyl ring were also more effective at activating PPAR than ciprofibrate. Considering compounds **280a–c**, **281a** and **b**, and **283a**, having OCH₃ groups in the 3- and 5-positions on the phenyl ring, showed that presence of different groups at the 4'-position determined the activity; thus, methoxy, ester, and phosphate are preferable. Compound **289a** with OH groups in the 3- and 5-positions on the phenyl ring did not show significant PPAR activation. Compound **289b** with an OCH₃ group in the 4'-position on the phenyl ring showed activation on PPAR α (>2-times), indicating that the OH groups in the 3- and 5-positions on the phenyl ring are highly effective for activity. The data indicated that the *E*-isomer is more favorable than the *Z*-isomer for activating PPAR α (Table 55).

8. Miscellaneous studies

Jung *et al.*¹⁰⁷ described the synthesis of stilbene compounds and assessed their antimalarial activity. The synthesis method of this research is similar to that in previous research.¹⁰⁵ Among the synthesized compounds, **290a** and **b** exhibited the highest

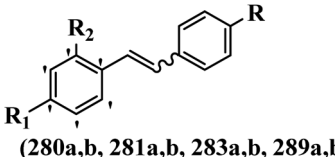
Table 54 Structures of stilbene derivatives



| Compound | <i>E/Z</i> | R ₁ | R ₂ | R ₃ | R ₄ | IC ₅₀ (μM) |
|-----------|------------|----------------|----------------|----------------|----------------|-----------------------|
| | | | | | | PTP1B |
| 270a | <i>E</i> | — | OH | OH | | 14.9 |
| 263a | <i>E</i> | — | OH | OH | | 260 |
| 264a | <i>E</i> | — | OH | OH | | 27.2 |
| 264b | <i>E</i> | — | OH | OH | | 101 |
| 272 | — | — | OH | OH | | — |
| 274a | — | — | OH | OH | | — |
| 274b | — | — | OH | OH | | — |
| 262 | <i>E</i> | — | OH | OH | | 25.6 |
| 271a | <i>Z</i> | — | OH | OH | | — |
| 276a | <i>E</i> | — | OH | OH | | 190 |
| 276b | <i>E</i> | OH | OH | — | | 168 |
| Molybdate | — | — | — | — | — | 21 |
| RK-682 | — | — | — | — | — | 45 |



Table 55 Synthetic compounds of pterostilbene analogues

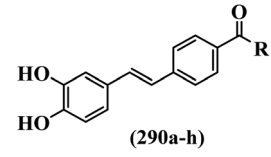


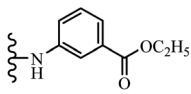
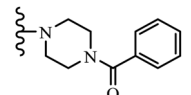
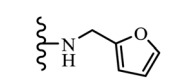
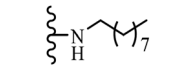
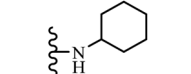
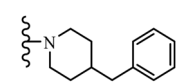
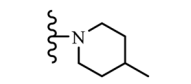
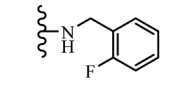
| Compound | <i>E/Z</i> | R | R ₁ | R ₂ |
|----------|------------|---------------------------------|------------------|------------------|
| 280a | <i>E</i> | NO ₂ | OCH ₃ | OCH ₃ |
| 280a | <i>Z</i> | NO ₂ | OCH ₃ | OCH ₃ |
| 280b | <i>E</i> | COOCH ₃ | OCH ₃ | OCH ₃ |
| 280b | <i>Z</i> | COOCH ₃ | OCH ₃ | OCH ₃ |
| 280c | <i>E</i> | OCH ₃ | OCH ₃ | OCH ₃ |
| 280c | <i>Z</i> | OCH ₃ | OCH ₃ | OCH ₃ |
| 281a | <i>E</i> | NH ₂ | OCH ₃ | OCH ₃ |
| 281a | <i>Z</i> | NH ₂ | OCH ₃ | OCH ₃ |
| 281b | <i>E</i> | COOH | OCH ₃ | OCH ₃ |
| 281b | <i>Z</i> | COOH | OCH ₃ | OCH ₃ |
| 283a | <i>E</i> | OPO ₃ H ₂ | OCH ₃ | OCH ₃ |
| 283b | <i>E</i> | OH | OCH ₃ | OCH ₃ |
| 289a | <i>Z</i> | OCH ₃ | OH | OH |
| 289b | <i>E</i> | OCH ₃ | OH | OH |

activity, and they were stronger than resveratrol, while they had lower activity compared to chloroquine. Compounds **290a** and **b** were significantly more active than **290c**, which had *N*-(furan-2-ylmethyl)aminocarbonyl. When the carbon chain was replaced with cycloalkane or aromatic ring, the activity was enhanced (*e.g.*, **290d** and **290e**). Also, the presence of *N*-(4-benzylpiperidine)carbonyl in **290f** resulted in lower activity compared to **290g**. In addition, **290c** compared to **290h** having *N*-(2-fluorobenzyl)aminocarbonyl showed a decrease in activity (Table 56).

Kang *et al.*¹⁰⁸ synthesized resveratrol analogues and reported their inhibitory activity against COX-1, COX-2, and NF-κB. Compounds **294a** against COX-1, **294b** against COX-2, and **294c** against NF-κB showed the highest activity among the analogues and they were stronger than resveratrol. All the potent COX-1 inhibitors contained a resorcinol ring, although in **294d**, the OH is replaced by OCH₃ groups. This trend, combined with the observation that the two resveratrol derivatives **294e** and **294f** are equipotent, suggests that for resveratrol to bind COX-1, both rings must rotate out of the plane of the alkene. Analogues **294d**, **294e**, and **294f** displayed potent inhibition against COX-1 and COX-2. This hypothesis is also supported by the SAR, where **294a** with C₂H₅ on carbon number one linker on the alkene was the most potent COX-1 inhibitor, whereas **294g**, which lacked a C₂H₅ substituent on the alkene, was 100-times less active. Although most of the active compounds had EDG in the R₁ position (*e.g.*, **294h** and **294a**), the COX-1 inhibitors showed that the phenol ring of resveratrol tolerates a wide variation of substitution. Thus, it seems reasonable that either the phenol of resveratrol occupies a hydrophobic and large cavity in the COX-1 active site or that area of resveratrol is solvent exposed in the

Table 56 Chemical structures of stilbene derivatives



| Compound | R | IC ₅₀ (μM) |
|-------------|---|-----------------------|
| 290a |  | 1.56 |
| 290b |  | 1.96 |
| 290c |  | 11.88 |
| 290d |  | 53.92 |
| 290e |  | 45.40 |
| 290f |  | 51.57 |
| 290g |  | 37.84 |
| 290h |  | 33.88 |
| Resveratrol | — | 0.02 |
| Chloroquine | — | 115.35 |

complex, which improved the effect of **294h** and **294a** slightly to the hydrophobic interactions. However, COX-2, unlike COX-1, recognizes a wide range of substitution patterns on R₃, all of which are EDG, indicating low COX-2 activity. R₁ of the potent COX-2 inhibitors, similar COX-1, showed no particular electronic preference and can accommodate the steric bulk of a naphthalene ring. Also, it is worth noting that the COX-2 inhibitors discovered in the assay showed high (>15 : 1) selectivity for COX-2 over COX-1 (*e.g.*, **294b** and **294i**). Based on the data, **294c** was more potent than resveratrol against NF-κB. Although the pseudo-symmetry of the resveratrol analogues lacking an alkene substituent complicates drawing firm conclusions, it is fairly clear that the catechol occupies the R₃ (resorcinol) site. In this case, it again appears that there is little selectivity for the R₁ ring, beyond a general preference for large and electron-rich rings, again suggesting either a hydrophobic or a solvent-exposed binding site for R₁ (Table 57).



Table 57 Structures of resveratrol analogues

(294a-i)

| Compound | R ₁ | R ₂ | R ₃ | IC ₅₀ (μM) | | |
|-------------|----------------|-------------------------------|----------------|-----------------------|-------|-------|
| | | | | COX-1 | COX-2 | NF-κB |
| 294a | | C ₂ H ₅ | | 0.17 | 3.3 | — |
| 294b | | CH ₃ | | 36.3 | 0.47 | — |
| 294c | | H | | — | — | 6.91 |
| 294d | | H | | 0.7 | 0.82 | 19.5 |
| 294e | | CH ₃ | | 1.9 | 1.57 | — |
| 294f | | CH ₃ | | 1.9 | 1.78 | — |
| 294g | | H | | 18.4 | — | — |
| 294h | | H | | 0.29 | 21.3 | — |
| 294i | | CH ₃ | | — | 1.74 | — |
| Resveratrol | — | — | — | 0.83 | 0.99 | 16.1 |

9. Conclusion

Stilbene, a natural compound having anti-microbial, antioxidant, anti-cancer, and anti-Alzheimer properties, has some issues, such as poor water solubility, which reduce its clinical use. Thus, due to the biological importance of this compound, the structure–activity relationship of stilbene derivatives and their biological activities were investigated in this review. The introduction of different substituents on the stilbene scaffold,

such as halogens and heterocycles, or the synthesis of hybrid molecules, affects the behavior of the compounds. The goal was to summarize the main structural changes and their associated activities that extend their activities compared to the standard compounds. The conclusions of the present investigations can be summarized as follows:

1. According to the results, the presence of different substitutions on phenyl rings improved the TXRT, anti-microbial, anti-cancer, antioxidant, and CYP inhibitory activity compared



to unsubstituted compounds. Alternatively, the presence of substitution on the carbon linker reduced the activity against cancer and COX.

2. The results indicated better antibacterial activity compared to antifungal activity. In addition, the findings showed that these compounds were more potent against Gram-positive bacteria than Gram-negative bacteria.

3. *Z*-Isomers displayed higher antibacterial, anti-cancer, Brdu incorporation and tubulin inhibitory activity compared to *E*-isomers. However, *E*-isomers showed better activity than *Z*-isomers on PPAR α activation and PTB1B inhibition.

4. The presence of bulky groups on phenyl rings increased the antioxidant activity, while they decreased the anti-microbial and BAE, VEGF, AChE, and HADC inhibitory activities. However, bulky groups on the phenyl rings did not show any change in anti-cancer, and tubulin inhibitory activity.

5. Increasing the number of substitutions on the phenyl rings improved the inhibitory activity of CYPs, but it had a negative effect on the anti-cancer activity. This factor showed no change in anti-microbial activity.

6. The presence of EWG on phenyl rings exhibited the highest inhibitory activity against PTB1B and CYPs and PPAR α activation. The presence of EDG on the phenyl rings showed the highest activity on induced apoptosis and against $\text{A}\beta_1\text{-}\beta_2$ -aggregation. Moreover, both EDG and EWG improved the activity against HADC, LSD1, COX, and cancer, and microbial activity.

7. Results showed that lipophilic groups on the phenyl rings enhanced the activity against VEGF, h-TERT, AChE, BuChE, mur ligase, CYPs, and PTB1B, and on PPAR α activation, antioxidant, and anti-cancer activity. Alternatively, hydrophilic groups increased the anti-microbe, induced apoptosis and BAE, LSD1, and COX inhibitory activity.

8. The aliphatic chain attached to the oxygen atom on the phenyl ring and the aliphatic chain on the substituted amide part of the phenyl ring showed better activity than the aliphatic ring on anti-microbial and antioxidant activity. Alternatively, the aliphatic ring on the substituted amide part of the phenyl ring exhibited higher activity than the aliphatic chain in terms of anti-malaria and anti-cancer activity.

9. Aromatic rings showed stronger anti-cancer activity and CYP inhibitory activity than heteroaromatic and aliphatic rings. However, heteroaromatic rings exhibited the highest antimalaria and antioxidant activity.

10. Aliphatic rings showed higher anti-microbial and anti-malaria activity and inhibition of HADC than aromatic rings.

11. The presence of amide groups showed inhibitory activity higher than that of amine groups against CYPs.

12. The antioxidant activity and inhibition of HADC of secondary amides were better than that of tertiary amides, while both secondary and tertiary amides showed the highest anti-cancer activity.

13. Expanding a conjugated system increased the inhibitory activity on $\text{A}\beta_1\text{-}\beta_2$ -aggregation; however, reduced PTB1B and PPAR α activation, while this process had the opposite result in anti-cancer activity.

14. The nature and position of substituents on the phenyl ring were significant for $\text{A}\beta_1\text{-}\beta_2$ -aggregation and AChE inhibitory activity. For example, substituents in the 4-position on the phenyl ring showed higher activity than in the 2- and 3-positions. Also, placing substituents on the phenyl or pyridine rings in all the positions resulted in the highest anti-microbial and anti-cancer activity and inhibition of CYPs and VEGF. The presence of groups in the 4-position was more potent than the 3-position on the coumarin ring anti-cancer activity. 3-Amidaxim on the phenyl ring displayed higher inhibitory activity than 4-amidaxim in the same position against LSD1. Changing the positions did not show any change in anti-microbial activity.

15. Increasing the chain length enhanced the AChE activity, but it had a negative effect on the BuChE inhibitory activity.

16. The presence of a bulky group on the phenyl ring showed strong antioxidant activity. However, the atom size had no effect on anti-microbial and anti-cancer activity.

Author contributions

Saghi Sepehri and Mohammad Mahdavi designed this review. Saghi Sepehri and Mina Khedmati drafted the manuscript. Faezeh Yousef-Nejad revised the manuscript. All authors contributed to the article and approved the submitted version.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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