Received: 5 May 2019 | Revised: 9 August 2019 | Accepted: 18 September 2019

DOI: 10.1002/bio.3719

REVIEW

WILEY LUMINESCENCE
The Journal of Biological and Chemical Luminescence

Recent chemo-/biosensor and bioimaging studies based on indole-decorated BODIPYs

Emrah Ozcan[1] | Hasan Huseyin Kazan[2] | Bunyemin Çoşut[1]

[1] Department of Chemistry, Faculty of Science, Gebze Technical University, Kocaeli, Turkey

[2] Department of Biological Sciences, Middle East Technical University, Ankara, Turkey

Correspondence
Bunyemin Çoşut, Department of Chemistry, Faculty of Science, Gebze Technical University, Fabrikalar Street, PO Box: 141, Gebze 41400 Kocaeli, Turkey.
Email: bc@gtu.edu.tr

Abstract

BODIPY is an important fluorophores due to its enhanced photophysical and chemical properties including outstanding thermal/photochemical stability, intense absorption/emission profiles, high photoluminescence quantum yield, and small Stokes' shifts. In addition to BODIPY, indole and its derivatives have recently gained attention because of their structural properties and particularly biological importance, therefore these molecules have been widely used in sensing and biosensing applications. Here, we focus on recent studies that reported the incorporation of indole-based BODIPY molecules as reporter molecules in sensing systems. We highlight the rationale for developing such systems and evaluate detection limits of the developed sensing platforms. Furthermore, we also review the application of indole-based BODIPY molecules in bioimaging studies. This article includes the evaluation of indole-based BODIPYs from synthesis to characterization and a comparison of the advantages and disadvantages of developed reporter systems, making it instructive for researchers in various disciplines for the design and development of similar systems.

KEYWORDS

indole, BODIPY, sensing, biosensing, bioimaging, metal, anion, thiol

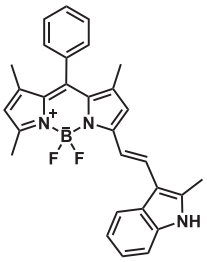
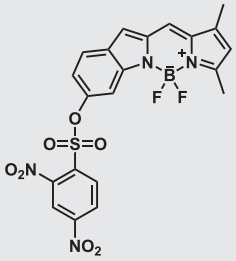
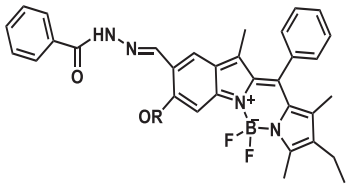
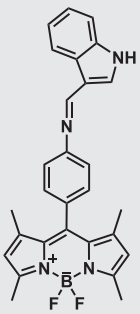
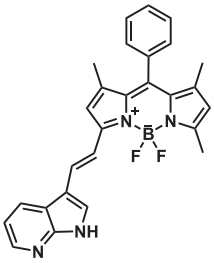
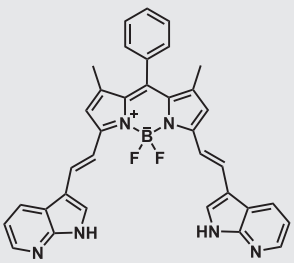
1 | INTRODUCTION

Over the last few decades, sensing systems have gained great attention due to their high selectivity, simplicity, and sensitivity.[1] In particular, fluorescence-based sensing platforms have been established and applied to detect diverse analytes in different disciplines such as biology, pharmacology, and medicine. The developed systems have enabled the detection of target molecules using a fluorescent signal or even by the naked eye in real time.[2] Although there have been numerous applications of fluorescent dyes as reporter systems in sensing platforms, these systems still require improvements to overcome the challenges and disadvantages of sensors.[3–5]

Supramolecular chemistry has great potential for fully or partially fulfilling demands in the development of novel sensors with enhanced properties such as lower detection limits and higher specificity and selectivity. Supramolecular structures serve as scaffolds in which target analytes are specifically bound and that result in the formation of a detectable signal.[6] Notably, two-fluorophore systems of supramolecular design have attracted the interest of researchers in more than one field.[7–10] As supramolecular approaches for the sensing applications are promising and very recent, the development of novel sensors not only for research purposes but also in commercial diagnostics will be anticipated.

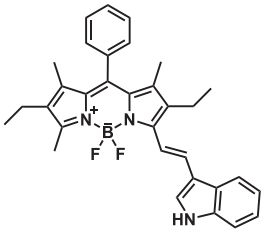
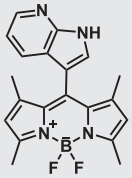
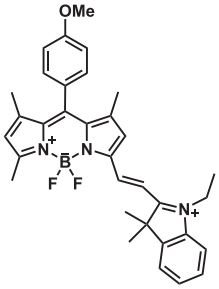
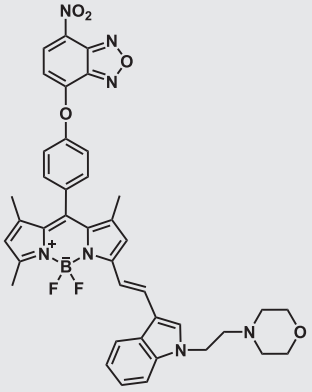
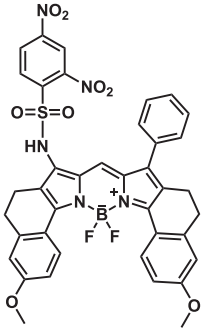
In the present article, we aim to: (i) summarize the studies that combine 4,4-difluoro-4-bora-3a,4a-diaza-s-indacene (BODIPY) and indole as reporter systems used in the detection of chemical or biological analytes; (ii) underlie the importance of BODIPY and indole in sensing systems; and (iii) overview applications of indole–BODIPY conjugates for different purposes other than sensing applications. Recent studies coupling indole and BODIPY for sensing systems are summarized and represented in Table 1 to elucidate the current state of this field and to encourage researchers to design and develop novel

TABLE 1 The indole–BODIPY compounds proposed for the detection of the related analytes and the limit of detection values

Analyte	Limit of detection	Compounds[a]	Reference
Copper	0.124 μM		[56]
Benzenethiol	9.5×10^{-7} M		[75]
Zinc	9.7×10^{-7} M	 R=H	[58]
Hydrogen sulfate	–		[64]
	75.6 μM		[65]
	44.27 μM		

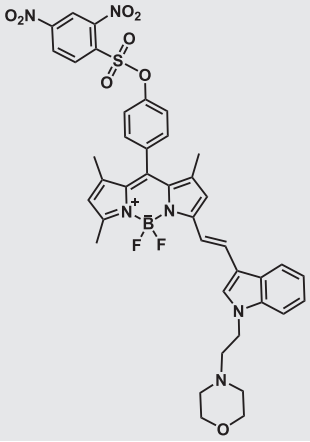
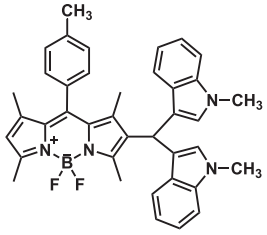
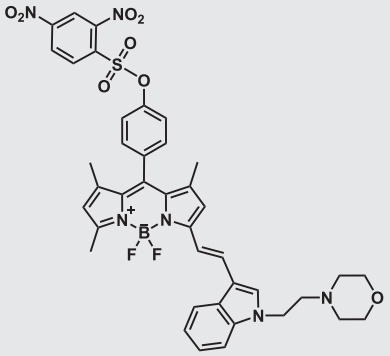
(Continues)

TABLE 1 (Continued)

Analyte	Limit of detection	Compounds[a]	Reference
Fluoride	36 μM		[45]
	1.21 μM		[69]
Cyanide	2.41 μM		[71]
GSH/Cys	0.64 μM/0.79 μM		[78]
Thiophenols	37 nM		[81]

(Continues)

TABLE 1 (Continued)

Analyte	Limit of detection	Compounds[a]	Reference
	9.8 nM		[82]
Mercury	3.3 x 10^{-7} M		[61]
Hydrogen sulfide	26 nM		[88]

[a]All compounds were re-adapted from related references using the ChemBioDraw Ultra v.14.0 program.

sensing platforms based on BODIPY and indole conjugate derivatives. The overviewed studies are classified with respect to the target analytes for better understanding and a structured organization.

1.1 | BODIPY in sensing systems

Fluorophores that are capable of emitting light at a particular wavelength upon excitation at a lower wavelength, have been widely used in various fields such as chemistry, engineering, and biological and material sciences.[11] The widespread use of fluorophores is due to various advantages such as their extremely sensitive and specific signals that provide lower detection limits and enable study at the single-molecule level.[12] Among a vast number of fluorescent dyes, BODIPY is one of the mostly studied fluorophores due to its unique properties of relatively high molar absorption coefficient and quantum yield, negligible triplet-state formation, narrow emission bandwidths, good solubility, resistance to self-aggregation in solution, excitation/emission wavelengths in the visible spectral region, and fluorescence lifetime (Figure 1). First and foremost, spectroscopic and photophysical properties of BODIPY and its derivatives could easily be tuned through modification and attachment of side residues.[13–15] As a result of their unique and enhanced photophysical and chemical characteristics, BODIPY derivatives have frequently been used in photodynamic therapy[16,17], protein tagging[18], imaging of biomolecules[19,20], for designing novel materials[21,22] and in energy transfer systems.[23–25] Moreover, BODIPY derivatives have widely been adapted to sensing platforms to detect various analytes such as ferric iron[26], glutathione[27], cyanide ions[28], fluoride[29], biological thiols[30], copper[31], and hypochlorite.[32] Such sensing systems are

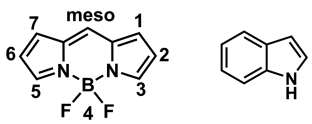


FIGURE 1 General structures of BODIPY (left) and indole (right)

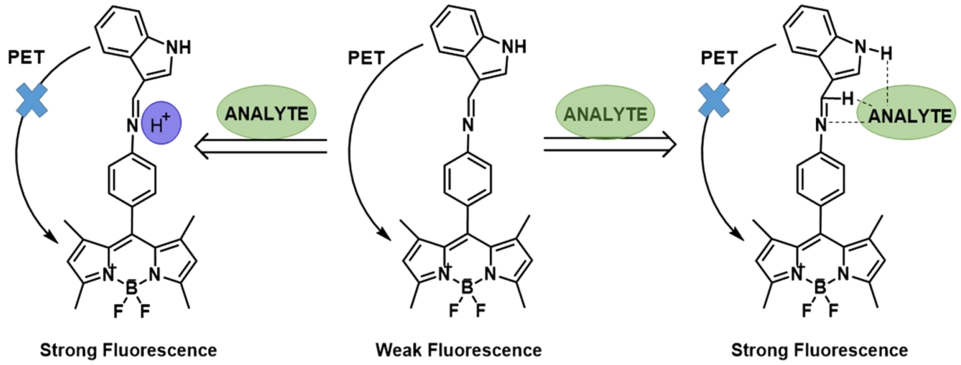


FIGURE 2 General sensing principle using PET mechanism occurring between BODIPY and indole moieties. Data adapted from[48]

still being developed, and novel sensors incorporating indole–BODIPY conjugates are still in high demand.

1.2 | Indoles in sensing systems

Indole is an electron-rich aromatic heterocyclic organic compound consisting of six-membered benzene ring fused to a five-membered pyrrole ring containing nitrogen (Figure 1). Indole is considered as an important molecule for biological applications as it is involved in various molecular pathways by acting as a building block for the amino acid, tryptophan and precursors for common therapeutics including anticancer, anti-inflammatory, and antiviral drugs.[33,34] Indole has 10 π-electrons, eight of which come from double bonds and two of which come from lone pairs of electrons of nitrogen, therefore it is regarded as an aromatic compound, according to Huckel's rule. Similar to the benzene ring, indole also undergoes electrophilic substitution reactions because of delocalization of excessive π-electrons.[35]

The most reactive position of indole for electrophilic substitution reactions is position 3 as it has the highest electron density according to molecular orbital calculations. In addition, indole molecules are reactive against strong acids due to their weak basic nature, therefore they undergo N-substitution under basic conditions through the slightly acidic N–H bond. This unique chemistry for indole makes it a potent and promising building block for various biological applications, notably for drug development.[36–39] In this context, indole has been used to develop fluorescent conjugates[40] and for sensing a wide range of analytes such as anions[41,42], more importantly acetate[43,44], fluoride[45], cyanide[46], and iodide.[47]

1.3 | Indole–BODIPY conjugates and sensing mechanism

As stated above, both BODIPY and indole have shown great potential in fluorescence-dependent sensing systems, mainly mediated by the photo-induced electron transfer (PET) phenomenon that occurs between the indole moiety and the BODIPY molecule (Figure 2). Therefore, the vast majority of all proposed mechanisms focuses on this principle and the ability of the indole moiety to bond through hydrogen bonding.

Apart from their sensing properties and applications, indole–BODIPY conjugates have been also used and studied in different disciplines for diverse purposes including assessing fluorescence properties[48–50], designing novel supramolecular scaffolds and structures[51–53], investigating optical characteristics[2], and engineering novel solar cells.[54] However, here we aim to emphasize the capability and practicability of indole–BODIPY conjugates for sensing chemical and/or biological entities and for bioimaging studies, therefore the above-mentioned applications in other fields were regarded as being out of the scope of the present article.

2 | INDOLE-BASED BODPY SYSTEMS FOR SENSING

2.1 | Metal ion sensing

2.1.1 | Copper sensing

Copper is a metallic element, and vital for biological systems and human health, with a crucial role in the function of diverse proteins and enzymes. Despite copper intake through the diet being essential for well-being, excess copper is a critical phenomenon linked to pathophysiological conditions.[55] The detection and quantification of copper particularly in biological systems, therefore, is fundamental to maintaining health. To this end, Tumay *et al.*[56] synthesized a novel 2-methyl-indole-3-carbaldehyde-conjugated BODIPY using the Knoevenagel condensation process for colorimetric and fluorometric detection of copper ions (Cu^{2+}). The synthesized conjugate was characterized using different analytical techniques including ^{1}H nuclear magnetic resonance (NMR), ^{13}C NMR, Fourier-transform infrared (FT-IR) spectroscopy, matrix-assisted laser desorption/ionization time-of-flight mass spectroscopy, and crystal X-ray diffraction, and this group showed that the developed indole-based BODIPY conjugate was specifically able to detect Cu^{2+}. Presence of Cu^{2+} was detected visually through change in the colour of the conjugate from purple to yellow, yielding a colorimetric signal. Fluorometric detection, conversely, was based on quenching of the fluorescent signal of the BODIPY moiety by Cu^{2+}, pointing out a 'turn-off' fluorescence system for Cu^{2+} sensing. Although the proposed system sensitively achieved

detection of Cu^{2+} and the detection limit was determined to be 0.124 μM, specificity was not fully evaluated by testing against different types of ions. In addition, biological evaluation of the conjugate was also performed, the conjugate was demonstrated to be able to stain both mammalian and bacterial cells, and did not exhibit any cytotoxicity.[56]

2.1.2 | Zinc sensing

Zinc is another biologically important element and is known to be involved in different biological processes including cell death mechanisms and protein function.[57] In an attempt to sensitively and specifically detect zinc ions (Zn^{2+}), Cao *et al*.[58] developed a novel complex consisting of indole-based BODIPY and salicylaldehyde benzoyl hydrazine as a chelating unit. Titration with Zn^{2+} resulted in re-orientation of the developed complex, and subsequently a significant increase in near-infrared (NIR) fluorescence. This phenomenon was explained by the authors as Zn^{2+} binding to the Schiff-base ligand possibly having deprotonated the phenol group and increase the rigidity of the C=N bond. Limit of detection of the developed system was reported as 9.7×10^{-7} M. The effectiveness and specificity of the complex was also tested *in vitro* against human cell lines.[58]

2.1.3 | Mercury sensing

Mercury is a heavy metal with a high toxicity against biological systems and living organisms. Due to increasing environmental pollution and health problems, mainly through industrialization, monitoring and detection of mercury is a major task, particularly in biological systems.[59,60] Although several detection techniques have been proposed, indole–BODIPY-based systems have emerged as a novel approach. For this purpose, Kaur *et al*.[61] designed an indole–BODIPY derivative for detection of mercury ions (Hg^{2+}). The detection principle relies on the fluorescent signal generated from interaction of Hg^{2+} with the electron-rich indolic units of BODIPY, whereas absence of Hg^{2+} results in PET. The developed complex was able to detect 3.3×10^{-7} M Hg^{2+}. The range of the complex was also demonstrated *in vitro* by testing human cell lines.[61]

2.2 | Anion sensing

2.2.1 | Hydrogen sulfate sensing

Hydrogen sulfate ions (HSO_4^-) are known to produce sulfate anions (SO_4^{2-}), which are toxic and have adverse effects on the skin, eyes, and respiratory system.[62] Despite the severe damage of sulfate anions to human health, a small number of sensing systems have been proposed so far. Accordingly, Li *et al*.[64] introduced a hydrogen sulfate anion sensor based on the indole–BODIPY conjugate using the CH_3CN solvent and CH_3CN-H_2O medium. The working principle of the proposed sensor system was based on an increase in fluorescence intensity of BODIPY in the presence of hydrogen sulfate in CH_3CN, whereas the fluorescence emission of BODIPY was transferred to the indole moiety using PET due to hydrogen bonding through the lone pairs of electrons on the indole moiety in the absence of hydrogen sulfate.[63] As in CH_3CN–H_2O medium, PET was prevented by protonation of the C=N– moiety of the indole–BODIPY complex. The system was shown to be highly selective for hydrogen sulfate anions.[64]

Our research group has also developed two hydrogen sulfate sensing systems based on BODIPY and azaindole moieties located at position 3 (mono) and positions 3 and 5 (distryl) of the BODIPY molecule. We showed that the position(s) of azaindole affected π-electron distribution, resulting in a turn-off model system for both compounds, but a lower limit of detection with distryl substitution (44.27 μM) compared with monosubstitution (75.6 μM). We also demonstrated that the compounds were not toxic towards human leukemic cell lines.[65]

2.2.2 | Fluoride and acetate sensing

Fluoride is one of the biologically important anions with various applications such as its roles in dental care and treatment of osteoporosis. In spite of its importance and diverse functions, excess amounts of fluoride have been associated with pathophysiological conditions.[66,67] Many research groups, therefore, were directed to develop various approaches for sensitive and specific detection of fluoride ions. For instance, Shiraishi *et al*.[68] proposed a novel indole–BODIPY conjugate based on a fluorescent turn-on signal that was triggered by binding of the fluoride anion to an indolic NH proton through hydrogen bonding. The detection limit for fluoride anions by this system was determined to be 36 μM.[45,68] The indole-based BODIPY complex for sensing of fluoride was also proposed by Mahapatra *et al*.[69] In an attempt to develop a more sensitive sensing system, they introduced a novel BODIPY–azaindole conjugate that was asserted to eliminate the limitations of the previously reported sensing systems. The working principle of the proposed system was colorimetric sensing of fluoride anions through deprotonation of indole moieties. The limit of detection of this novel system was calculated to be 1.21 μM, and the system was found to be specific for acetate anions, as well. As a part of biological investigations, this group also evaluated the cytotoxicity and bio-practicability of the BODIPY–azaindole conjugate. The system was shown to be nontoxic, and specifically generated a fluorescence signal on human cells in response to the presence of fluoride.[69]

2.2.3 | Cyanide sensing

Cyanide is one of the most hazardous chemical compounds. It causes overproduction of reactive oxygen species in the mitochondria and damages the respiratory tract by acting as an inhibitor of aerobic respiration.[70] Extreme toxicity and increasing environmental pollution resulting from the industrial use of cyanide necessitate the development of more sensitive methods as an alternative to the current detection systems. Recently, Kang *et al*.[71] described an indole-based BODIPY sensing system to detect cyanide and that relied on the prevention of intramolecular charge transfer by cyanide attack on the indolium group in the structure. The proposed system was determined

to be very sensitive with a detection limit of 2.41 μM, and was also effective on human cells.[71]

2.3 | Thiol sensing

2.3.1 | Benzenethiol sensing

Thiols are organosulfur compounds with the formula R–SH, and have significant roles in a wide range of areas including petrochemistry, the food industry, and medicine.[72] Benzenethiols conversely have been reported to be functional in the production of polymers, pharmaceuticals, and pesticides. Despite the wide uses of these compounds, they also exert toxic effects[73], therefore their selective and sensitive detection in different matrices constitutes a major task. The number of available fluorescence-based sensing systems for benzenethiols is very limited due to specificity and selectivity issues resulting from the similar physical and chemical properties of aliphatic thiols and benzenethiols.[74] Considering the importance of benzenethiol detection and problems associated with the current fluorescent sensors, Zhao *et al*.[75] designed an inducible indole-based BODIPY conjugated to the 2,4-dinitrobenzenesulfonyl group as a reporter system for benzenethiols (Bodipy-1). The principle of detection of this system was based on the release of the BODPIY moiety from the conjugate using aromatic nucleophilic substitution (Bodipy-2) through the action of thiolate anions of benzenethiols in a pH-dependent manner that subsequently altered the emission spectrum. The proposed system was shown to be highly specific for benzenethiols and sensitive, with a limit of detection of 9.5×10^{-7} M.[75]

2.3.2 | Glutathione and cysteine sensing

Glutathione (GSH) and cysteine (Cys) are thiol-containing biomolecules that have vital roles in various molecular mechanisms including intracellular redox state, cellular metabolism, and signal transduction. Due to their biologically importance and involvement in different pathways, they should exist at definite levels for maintenance of the homeostasis. Abnormal levels of GSH and Cys have been proven to be correlated with a broad range of disorders such as cancer, cardiovascular diseases, inflammatory diseases, and neurological diseases.[76,77] Despite the high interest in GSH and Cys as an indicator of redox balance, a common method for detection and quantification of these molecules in biological samples has still not been proposed. One method that was developed for fluorescence-based sensing of GSH and Cys in both human plasma and cell lines was based on indole–BODIPY-conjugated 7-nitrobenzofurazan (NBD). The NBD moiety in the conjugate acts as a GSH- and Cys-binding group through an ether bond, whose substitution with the nucleophilic thiolate group of GSH or Cys resulted in the release of the indole–BODIPY complex, enabling the formation of a detectable fluorescence signal. Detection limits were reported as 0.79 μM and 0.64 μM for Cys and GSH, respectively.[78,79]

2.3.3 | Thiophenol sensing

Thiophenols (PhSHs) are considered to be the simplest aromatic thiols and frequently used in the proposed production of pharmaceuticals, pesticides, polymers, and various industrial products. In spite of their diverse synthetic utilities and practical values, thiophenols are considered to be one of the prioritized pollutants due to their toxic effects on aquatic organisms, and liver, kidney and central nervous systems in humans.[80] It is important, therefore, to develop sensitive and selective methods to monitor thiophenols, particularly for chemical, biological, and environmental sciences. In this context, Shao *et al*.[81] developed an indole molecule incorporating a BODIPY- and 2,4-dinitrobenzenesulfony (DNBS) turn-on system that specifically yielded a fluorescence signal as a response to thiophenols. Analytical performance of the developed sensing system was tested in two different solutions, and the limit of detection was found to be 4 μM and 37 nM in acetonitrile/PBS and 1% Tween 20 solution, respectively. The biological efficacy of the system was also demonstrated by sensing PhSH in mammalian cells.[81] Similarly, Wu *et al*.[82] described an improved PhSH sensor based on indole, BODIPY and DNBS with a shorter assay duration of 8 min and lower detection limit of 9.8 nM.[82]

2.4 | Hydrogen sulfide sensing

Hydrogen sulfide (H_2S), known as a toxic gas, has recently emerged as an important gaseous transmitter. H_2S is endogenously generated from cysteine and acts as a novel critical mediator in the nervous system, cardiovascular system, modulation of the metabolic rate and blood pressure, inflammatory regulation and different biological signalling pathways.[83–85] Nonetheless, H_2S production at abnormal levels has been associated with cancer and neuropathological conditions such as Parkinson's disease, Huntington's disease and Alzheimer's disease.[86,87] Therefore, detection and quantification of H_2S in biological systems, including human fluids and living cells, are critical for early diagnosis of these disorders. In this sense, Pan *et al*.[88] proposed an indole-based BODIPY conjugated with morpholine and DNBS for the rapid and sensitive detection of hydrogen sulfide in aqueous solutions and living cells. The proposed sensing system achieved selective and sensitive detection of hydrogen sulfide by a fluorescence turn-on principle based on the prevention of PET between BODIPY and indole molecules. They further evaluated the stability of the developed system over a wide pH range and found that detection of hydrogen sulfide by this novel conjugate was sensitive to increased pH conditions. Efficacy was also confirmed *in vitro* by testing on human cells, and the detection limit was reported to be 26 nM.[88]

3 | BIOIMAGING STUDIES

In the last decades, many researchers have focused on developing diverse molecular bioimaging techniques for visualization and characterization of cellular functions, understanding complex interactions of molecular processes, and measuring these processes in living

organisms. Among many proposed imaging techniques such as electron, optical and X-ray microscopy and magnetic resonance imaging, optical imaging based on fluorescence has emerged as a sensitive and accurate method using different wavelengths emitted by fluorescent molecules.[89,90] Due to limitations of the conventional fluorescent probes, indole-decorated BODIPY scaffolds were proposed as a novel system in the design of bioimaging probes for visualization of different analytes. For this purpose, Dong *et al.*[91] synthesized two novel *meso*-indoles substituted by NO_2 or NH_2 moieties linked to the BODIPY molecule. For chemical and photochemical characterization, they tested these compounds on a human leukemia cell line, HL-60, and showed that compounds easily internalized into the cells, and stained mostly the membrane and cytoplasm, but not nucleus in the fluorescence range 510–550 nm, without exerting any toxicity on the cells. However, biological studies were inadequate due to lack of appropriate solvent control and information about the solvent used in these studies.[91]

In addition, indole molecules have been used to modulate fluorescence properties of the BODIPY conjugates for *in vivo* imaging. For instance, Sansalone *et al.*[92] developed a novel system in which irreversible cleavage of the oxazine ring within the BODIPY complex using photo-induction that enabled the residue to interact with the indole molecule and subsequently extend fluorescence excitation and emission spectra. They also tested this controllable system on *Drosophila melanogaster* embryos, and demonstrated the potential of this system for *in vivo* applications without any autofluorescence issue.[92] A similar approach was applied to nanoparticles modified using photo-inducible BODIPY molecules and the indole moiety; biological evaluation of photo-inducible nanoparticles was evaluated on *Caenorhabditis elegans*.[93]

4 | CONCLUSIONS AND FUTURE PERSPECTIVE

BODIPY is an important fluorophore that possesses improved photophysical and chemical properties. It is frequently adapted for the design of novel supramolecular structures that are employed in diverse areas. Among various fields of application, BODIPY derivatives have been widely used in sensing platforms by conjugation of numerous molecules that are designated according to the purpose of the study and analyte of interest. Indole is one of the most widely used conjugates due to its unique chemistry and biological importance. In this article, we aimed to focus on the indole molecule and provide an overview of studies incorporating indole and BODIPY for sensing purposes. The primary reason for the use of indole together with BODIPY was underlined using PET, in which indole molecules limit the fluorescence properties of BODIPY derivatives. Due to its ability to form hydrogen bonds through its side chains, indole molecules tend to alter conformation and reorient the structure of the complex, subsequently resulting in the release of BODIPY fluorescence. By employing this principle, many researchers have introduced novel sensing systems for rapid, specific, and sensitive detection of a broad range of analytes, including copper, benzenethiol, zinc, hydrogen sulfate, fluoride, acetate, glutathione, cysteine, thiophenols, mercury, and hydrogen sulfate. This article emphasizes the fact that, despite indole and BODIPY have a great potential for diagnostic and sensing purposes, there is only a limited number of published studies that incorporate these molecules. Therefore, novel compounds for sensing and/or bioimaging studies based on indole-containing BODIPY molecules need to be developed. Methodologies through these studies should be well defined and provide the rationale necessary for biological experiments. Finally, we anticipate that this review article will be useful for exploration of potential indole–BODIPY complexes for sensing platforms and pave the way for new studies.

ACKNOWLEDGEMENTS

We would like to thank Onur Bulut (Biological Sciences, Middle East Technical University, Ankara) for critical reading.

ORCID

Bunyemin Çoşut https://orcid.org/0000-0001-6530-0205

REFERENCES

[1] J. Wu, W. Liu, J. Ge, H. Zhang, P. Wang, *Chem. Soc. Rev.* **2011**, *40*, 3483.

[2] L. Wang, Y. Qu, J. Xu, J. Cao, C. Zhao, *Tetrahedron Lett.* **2016**, *57*, 1605.

[3] J. Li, C. Yin, F. Huo, *RSC Adv.* **2015**, *5*, 2191.

[4] W. Shi, X. Ji, S. Zhang, M. Wei, D. G. Evans, X. Duan, *J. Phys. Chem. C* **2011**, *115*, 20433.

[5] G. Tang, S. S. Chen, P. E. Shaw, K. Hegedus, X. Wang, P. L. Burn, P. Meredith, *Polym. Chem.* **2011**, *2*, 2360.

[6] L. You, D. Zha, E. V. Anslyn, *Chem. Rev.* **2015**, *115*, 7840.

[7] N. R. Chereddy, P. Nagaraju, M. N. Raju, K. Saranraj, S. Thennarasu, V. J. Rao, *Dyes Pigm.* **2015**, *112*, 201.

[8] L. Figueroa, V. M. Shkryl, L. A. Blatter, E. Rios, *PLoS ONE* **2013**, *8*, e55778.

[9] C. C. Woodroofe, S. J. Lippard, *J. Am. Chem. Soc.* **2003**, *125*, 11458.

[10] C. C. Woodroofe, A. C. Won, S. J. Lippard, *Inorg. Chem.* **2005**, *44*, 3112.

[11] B. Mahler, P. Spinicelli, S. Buil, X. Quelin, J. P. Hermier, B. Dubertret, *Nat. Mater.* **2008**, *7*, 659.

[12] A. C. Benniston, G. Copley, *Phys. Chem. Chem. Phys.* **2009**, *11*, 4124.

[13] N. Boens, V. Leen, W. Dehaen, *Chem. Soc. Rev.* **2012**, *41*, 1130.

[14] Y. Ni, J. Wu, *Org. Biomol. Chem.* **2014**, *12*, 3774.

[15] G. Ulrich, R. Ziessel, A. Harriman, *Angew. Chem. Int. Ed. Engl.* **2008**, *47*, 1184.

[16] S. G. Awuah, J. Polreis, V. Biradar, Y. You, *Org. Lett.* **2011**, *13*, 3884.

[17] A. Kamkaew, S. H. Lim, H. B. Lee, L. V. Kiew, L. Y. Chung, K. Burgess, *Chem. Soc. Rev.* **2013**, *42*, 77.

[18] L. C. Rezende, F. S. Emery, *Orbital Electron. J. Chem.* **2013**, *5*, 62.

[19] H. H. Kazan, E. Özcan, E. T. Eçik, B. Çoşut, *ChemistrySelect* **2018**, *3*, 2962.

[20] T. Kowada, H. Maeda, K. Kikuchi, *Chem. Soc. Rev.* **2015**, *44*, 4953.

[21] O. Garcia, R. Sastre, D. Del Agua, A. Costela, I. Garcia-Moreno, *Chem. Mater.* **2006**, *18*, 601.

[22] M. Ozdemir, D. Choi, G. Kwon, Y. Zorlu, B. Çoşut, H. Kim, A. Facchetti, C. Kim, H. Usta, *ACS Appl. Mater. Interfaces* **2016**, *8*, 14077.

[23] B. Çoşut, *Dyes Pigm.* **2014**, *100*, 11.

[24] E. T. Eçik, E. Özcan, H. Kandemir, I. F. Sengul, B. Çoşut, *Dyes Pigm.* **2017**, *136*, 441.

[25] C. Y. Lee, O. K. Farha, B. J. Hong, A. A. Sarjeant, S. T. Nguyen, J. T. Hupp, *J. Am. Chem. Soc.* **2011**, *133*, 15858.

[26] B. Sui, S. Tang, T. Liu, B. Kim, K. D. Belfield, *ACS Appl. Mater. Interfaces* **2014**, *6*, 18408.

[27] L. Y. Niu, Y. S. Guan, Y. Z. Chen, L. Z. Wu, C. H. Tung, Q. Z. Yang, *J. Am. Chem. Soc.* **2012**, *134*, 18928.

[28] Z. Ekmekci, M. D. Yilmaz, E. U. Akkaya, *Org. Lett.* **2008**, *10*, 461.

[29] X. Cao, W. Lin, Q. Yu, J. Wang, *Org. Lett.* **2011**, *13*, 6098.

[30] M. Isik, T. Ozdemir, I. S. Turan, S. Kolemen, E. U. Akkaya, *Org. Lett.* **2012**, *15*, 216.

[31] X. Qi, E. J. Jun, L. Xu, S. Kim, J. S. J. Hong, Y. J. Yoon, J. Yoon, *J. Org. Chem.* **2006**, *71*, 2881.

[32] S. T. Manjare, J. Kim, Y. Lee, D. G. Churchill, *Org. Lett.* **2013**, *16*, 520.

[33] S. Biswal, U. Sahoo, S. Sethy, H. Kumar, M. Banerjee, A. J. Pharm, *Clin. Res.* **2012**, *5*, 1.

[34] B. A. Moyer, F. V. Sloop Jr., C. J. Fowler, T. J. Haverlock, H. A. Kang, L. H. Delmau, D. M. Bau, M. A. Hossain, K. Bowman-James, J. A. Shriver, N. L. Bill, *Supramol. Chem.* **2010**, *22*, 653.

[35] S. Lakhdar, M. Westermaier, F. Terrier, R. Goumont, T. Boubaker, A. R. Ofial, H. Mayr, *J. Org. Chem.* **2006**, *71*, 9088.

[36] C. Kalinski, M. Umkehrer, J. Schmidt, G. Ross, J. Kolb, C. Burdack, W. Hiller, S. D. Hoffmann, *Tetrahedron Lett.* **2006**, *47*, 4683.

[37] S. Oishi, T. Watanabe, J. I. Sawada, A. Asai, H. Ohno, N. Fujii, *J. Med. Chem.* **2010**, *53*, 5054.

[38] T. Sravanthi, S. Manju, *Eur. J. Pharm. Sci.* **2016**, *91*, 1.

[39] P. Tao, Y. Jia, *Chem. Comm.* **2014**, *50*, 7367.

[40] R. M. Bouldin, A. Singh, M. Magaletta, S. Connor, J. Kumar, R. Nagarajan, *Bioengineering* **2014**, *1*, 246.

[41] K. J. Chang, D. Moon, M. S. Lah, K. S. Jeong, *Angew. Chem. Int. Ed.* **2005**, *117*, 8140.

[42] R. Manivannan, A. Satheshkumar, E. S. H. El-Mossalamy, L. M. Al-Harbi, S. A. Kosa, K. P. Elango, *New J. Chem.* **2015**, *39*, 3936.

[43] J. Shao, Y. Wang, H. Lin, J. Li, H. Lin, *Sens. Actuators, B Chem.* **2008**, *134*, 849.

[44] Y. Wang, H. Lin, J. Shao, Z. S. Cai, H. K. Lin, *Talanta* **2008**, *74*, 1122.

[45] Y. Shiraishi, H. Maehara, T. Sugii, D. Wang, T. Hirai, *Tetrahedron Lett.* **2009**, *50*, 4293.

[46] P. Jayasudha, R. Manivannan, S. Ciattini, L. Chelazzi, K. P. Elango, *Sens. Actuators, B Chem.* **2017**, *242*, 736.

[47] K. R. Rathikrishnan, V. K. Indirapriyadharshini, S. Ramakrishna, R. Murugan, *Tetrahedron* **2011**, *67*, 4025.

[48] S. Shimizu, A. Murayama, T. Haruyama, T. Iino, S. Mori, H. Furuta, N. Kobayashi, *Chem. Eur. J.* **2015**, *21*, 12996.

[49] C. Yu, Y. Xu, L. Jiao, J. Zhou, Z. Wang, E. Hao, *Chem. Eur. J.* **2012**, *18*, 6437.

[50] A. E. Sadak, A. C. Goren, O. A. Bozdemir, N. Saracoglu, *ChemistrySelect* **2017**, *2*, 10512.

[51] R. Jiang, X. Yang, D. Wu, *Org. Biomol. Chem.* **2017**, *15*, 6888.

[52] L. Luo, D. Wu, W. Li, S. Zhang, Y. Ma, S. Yan, J. You, *Org. Lett.* **2014**, *16*, 6080.

[53] Y. Zhang, S. Swaminathan, S. Tang, J. Garcia-Amoros, M. Boulina, B. Captain, J. D. Baker, F. M. Raymo, *J. Am. Chem. Soc.* **2015**, *137*, 4709.

[54] I. Bulut, Q. Huaulme, A. Mirloup, P. Chavez, S. Fall, A. Hebraud, S. Mery, B. Heinrich, T. Heiser, P. Leveque, N. Leclerc, *ChemSusChem* **2017**, *10*, 1878.

[55] J. Osredkar, N. Sustar, *J. Clin. Toxicol. S.* **2011**, *3*, 2161.

[56] S. O. Tümay, E. Okutan, I. F. Sengul, E. Ozcan, H. Kandemir, T. DOruk, M. Cetin, B. Cosut, *Polyhedron* **2016**, *117*, 161.

[57] B. L. Vallee, D. S. Auld, *Acc. Chem. Res.* **1993**, *26*, 543.

[58] J. Cao, C. Zhao, X. Wang, Y. Zhang, W. Zhu, *Chem. Comm.* **2012**, *48*, 9897.

[59] R. A. Bernhoft, *J. Environ. Public Health* **2012**, *2012*, 460508.

[60] C. F. Macrae, P. R. Edgington, P. McCabe, E. Pidcock, G. P. Shields, R. Taylor, M. Towler, J. V. D. Streek, *J. Appl. Crystallogr.* **2006**, *39*, 453.

[61] N. Kaur, P. Kaur, G. Bhatia, K. Singh, J. Singh, *RSC Adv.* **2016**, *6*, 82810.

[62] P. Saluja, N. Kaur, N. Singh, D. O. Jang, *Tetrahedron* **2012**, *68*, 8551.

[63] Y. Gabe, Y. Urano, K. Kikuchi, H. Kojima, T. Nagano, *J. Am. Chem. Soc.* **2004**, *126*, 3357.

[64] Q. Li, Y. Guo, S. Shao, *Analyst* **2012**, *137*, 4497.

[65] G. Kesan, B. Topaloglu, E. Ozcan, H. H. Kazan, E. T. Ecik, E. Senkuytu, I. F. Sengul, H. Kandemir, B. Cosut, *Spectrochim. Acta, A Mol. Biomol. Spectrosc.* **2019**, *213*, 73.

[66] D. Chlubek, S. Poland, *Fluoride* **2003**, *36*, 217.

[67] L. M. A. Tenuta, J. A. Cury, *Braz. Oral Res.* **2010**, *24*, 9.

[68] X. Bao, Y. Zhou, B. Song, *Mini Rev. Org. Chem.* **2011**, *8*, 17.

[69] A. K. Mahapatra, R. Maji, K. Maiti, S. S. Adhikari, C. D. Mukhopadhyay, D. Mandal, *Analyst* **2014**, *139*, 309.

[70] L. L. Long, M. Y. Huang, N. Wang, Y. J. Wu, K. Wang, A. H. Gong, Z. J. Zhang, J. L. Sessler, *J. Am. Chem. Soc.* **2018**, *140*, 1870.

[71] J. Kang, F. Huo, Y. Zhang, J. Chao, T. E. Glass, C. Yin, *Spectrochim. Acta, A Mol. Biomol. Spectrosc.* **2019**, *209*, 95.

[72] X. Chen, Y. Zhou, X. Peng, J. Yoon, *Chem. Soc. Rev.* **2010**, *39*, 2120.

[73] X. Wang, J. Cao, C. Zhao, *Org. Biomol. Chem.* **2012**, *10*, 4689.

[74] W. Jiang, Q. Fu, H. Fan, J. Ho, W. Wang, *Angew. Chem. Int. Ed. Engl.* **2007**, *119*, 8597.

[75] C. Zhao, Y. Zhou, Q. Lin, L. Zhu, P. Feng, Y. Zhang, J. Cao, *J. Phys. Chem., B* **2010**, *115*, 642.

[76] C. Hwang, A. J. Sinskey, H. F. Lodish, *Science* **1992**, *257*, 1496.

[77] P. K. Pullela, T. Chiku, M. J. Carvan, D. S. Sem, *Anal. Biochem.* **2006**, *352*, 265.

[78] J. Pan, Y. Zhang, J. Xu, J. Liu, L. Zeng, G. M. Bao, *RSC Adv.* **2015**, *5*, 97781.

[79] L. Yi, Z. Xi, *Org. Biomol. Chem.* **2017**, *15*, 3828.

[80] M. Asadollahi-Baboli, *Environ. Toxicol. Pharmacol.* **2012**, *34*, 826.

[81] X. Shao, R. Kang, Y. Zhang, Z. Huang, F. Peng, J. Zhang, Y. Wang, F. Pan, W. Zhang, W. Zhao, *Anal. Chem.* **2014**, *87*, 399.

[82] F. Wu, H. Wang, J. Xu, H. Q. Yuan, L. Zeng, G. M. Bao, *Sens. Actuators, B Chem.* **2018**, *254*, 21.

[83] B. Geng, L. Chang, C. Pan, Y. Qi, J. Zhao, Y. Pang, J. Du, C. Tang, *Biochem. Biophys. Res. Commun.* **2004**, *318*, 756.

[84] G. Yang, L. Wu, B. Jiang, W. Yang, J. Qi, K. Cao, Q. Meng, A. K. Mustafa, W. Mu, S. Zhang, S. H. Snyder, *Science* **2008**, *322*, 587.

[85] R. C. Zanardo, V. Brancaleone, E. Distrutti, S. Fiorucci, G. Cirino, J. L. Wallace, R. C. Zanardo, V. Brancaleone, E. Distrutti, S. Fiorucci, G. Cirino, *FASEB J.* **2006**, *20*, 2118.

[86] K. Eto, T. Asada, K. Arima, T. Makifuchi, H. Kimura, *Biochem. Biophys. Res. Commun.* **2002**, *293*, 1485.

[87] A. Papapetropoulos, A. Pyriochou, Z. Altaany, G. Yang, A. Marazioti, Z. Zhou, M. G. Jeschke, L. K. Branski, D. N. Herndon, R. Wang, C. Szabo, *Proc. Natl. Acad. Sci. USA.* **2009**, *106*, 21972.

[88] J. Pan, J. Xu, Y. Zhang, L. Wang, C. Qin, L. Zeng, Y. Zhang, *Spectrochim. Acta, A Mol. Biomol. Spectrosc.* **2016**, *168*, 132.

[89] J. W. Lim, S. U. Son, E. K. Lim, Recent advances in bioimaging for cancer research, in M. S. Ghamsari (Ed), *State of the Art in Nanobioimaging*. London: IntechOpen. **2017**, 11–26.

[90] F. W. Pratiwi, C. W. Kuo, B. C. Chen, P. Chen, *Nanomedicine* **2019**, *14*, 1759.

[91] B. Dong, K. Zhong, Y. Lu, *Dyes Pigm.* **2019**, *164*, 156.

[92] L. Sansalone, S. Tang, J. Garcia-Amoros, Y. Zhang, S. Nonell, J. D. Baker, B. Captain, F. M. Raymo, *ACS Sens.* **2018**, *3*, 1347.

[93] S. Tang, Y. Zhang, P. Dhakal, L. Ravelo, C. L. Anderson, K. M. Collins, F. M. Raymo, *J. Am. Chem. Soc.* **2018**, *140*, 4485.

How to cite this article: Ozcan E, Kazan HH, Çoşut B. Recent chemo-/biosensor and bioimaging studies based on indole-decorated BODIPYs. *Luminescence*. 2019;1–10. https://doi.org/10.1002/bio.3719