Chapagain *et al. Sustainable Environment Research* (2022) 32:5
https://doi.org/10.1186/s42834-021-00115-6

Sustainable Environment Research

RESEARCH Open Access

Analyzing the relationship between water pollution and economic activity for a more effective pollution control policy in Bali Province, Indonesia

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Abstract

An adequate water supply is essential for the continued and sustainable growth of the Balinese economy. In addition to mounting water demand, Bali's water supply has been constrained by high levels of water pollution. Despite being paid great attention, Bali's earlier efforts to control water pollution yet to prove effective, mainly owing to their reliance on traditional methods and regulations that focus on water pollution being linked to discrete sets of economic activity (e.g., processing industries, livestock farming, and hotels). However, an economy of a region/country comprises a set of sectoral activities, which are interconnected through supply chains; thus, water pollution could be well explained by examining the entire sectoral economic activities and their environmental performance. Therefore, determining the structural relationships between water pollution and economic activity serves as an important basis for more effective forms of pollution control for the Balinese economy. In this study, accordingly, we employed an environmentally extended input–output model to establish the links between water pollution and the production processes of the entire economy. Using biochemical oxygen demand (BOD) as a proxy for water quality in our analysis, we estimated that 246.9 kt of BOD were produced from Bali's economic activity in 2007. Further, we identified the chief BOD-emitting sectors and found that intermediate demand and household demand were the major causes of BOD discharge in the economy. We also accounted for the indirect role of each sector in total BOD emissions. Moreover, we categorized the sectors into four groups based on their direct and indirect BOD emission characteristics and offered appropriate policy measures for each group. Managing demand (i.e., lowering household consumption and exports) and shifting input suppliers (i.e., from polluters to non-polluters) are effective measures to control pollution for Categories I and II, respectively; clean production and abatement is advised for Category III; and a hybrid approach (i.e., demand management and abatement technology) is recommended for Category IV.

Keywords: Biochemical oxygen demand (BOD), Bali, Environmentally extended input–output (EEIO) modeling, Direct pollution, Water policy, Water pollution

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1 Introduction

Global water resources are under immense pressure owing to increases in water demand that are due to population growth and expanded industrial and economic activity. The stress has been further exacerbated by increasing water pollution [1]. Florke et al. [2] reported that the global withdrawal of domestic and industrial water increased by 77.7% with 300–1345 km^3 withdrawn over the last six decades (1950–2010); of the extracted water, 88% was ultimately returned to the system as wastewater with limited treatment. The situation is a serious concern in the Asia–Pacific region, which is undergoing rapid economic growth. Consequently, the region's natural environment is being distressed by the consumption of huge amounts of water, the release of waste and wastewater, and the expansion of pollution-prone industries [3].

Bali, Indonesia, a famous global tourist destination in the Asia–Pacific region [4, 5], has undergone rapid economic growth over the last three decades [6]. The Balinese economy is traditionally supported by agriculture; however, it has recently become dominated by the tourism sector [7]. In 2018, tourism (i.e., accommodation and food services) accounted for 23.3% of Bali's gross regional domestic product (GRDP), while agriculture, forestry, and fisheries accounted for 13.8% of its GRDP [5]. Bali's population was reported to be 4,466,600 as of 2021 with an average annual growth rate of 1.24% (2010–2018) [5, 8]. Rapid economic growth, population growth, and poor water management will likely cause more serious water shortages in the future [9]. Despite its substantial potential for natural renewable water, Bali's water supply is compromised because of an elongated coastland, lower groundwater potential, and a high population density (FAO 2003 as cited in Strauß [4]). By 2025, water consumption is projected to expand by 70% [4, 10]. Water shortages are reported to reduce food production and employment on the island, while both tourism and agriculture rely on an adequate water supply [10, 11].

Environmental degradation and pollution have put Bali's water resources at significant risk [9, 10]. Water quality has been affected by the recent socio-economic development. For example, an increase in population density leads to increased levels of water pollutants, such as organic substances (biochemical oxygen demand (BOD)) and fecal matter (*Escherichia coli*), in river water. Similarly, built-up areas, which have been increasing recently, have impacted the river water quality negatively by elevating heavy metals (i.e., nickel and lead) and turbidity [12]. Suteja et al. [13] reported that the two major rivers—namely, the Badung and Mati Rivers—were the primary source of chromium deposits in the river estuary of Benoa Bay. A significant amount of water pollutants is reportedly discharged in water bodies because of intensive agricultural practices, including the excessive use of fertilizers and plant protection chemicals [14]. Nitrate and phosphate contamination prevails in all the rivers, although the contamination levels vary depending on the river and season. The highest loadings of nitrates and phosphates were reported as 4.39 and 6.98 t d^{-1}, respectively, in the Mati River, which drains into Benoa Bay, in the dry season, thereby causing the water quality to exceed the standard for marine biota [15]. River water, namely, that of the Ayung and Badung Rivers, is the major source of drinking water and irrigation. Meeting water quality standards, such as having a BOD of 2 and 12 $mg\ L^{-1}$, respectively, for class I (i.e., potable water supply) and class IV (i.e., irrigation use), as stipulated in the water quality management and control measures of the Indonesian Government Regulations number 22 of 2021 [16], is challenging.

The island of Bali operates two centralized wastewater treatment plants with a total capacity of 61,000 (51,000 + 10,000) $m^3\ d^{-1}$ [9, 14] as well as some community-based decentralized wastewater treatment systems with limited capacities [17]. Since the current treatment capacity is less than 10% of the total urban wastewater production (642,000 $m^3\ d^{-1}$, as estimated in 2012) [9], a vast portion of wastewater from households, industries, hotels, restaurants, business, and complexes, and waste and runoff of agriculture and livestock directly drains into nearby canals, rivers, and ocean [10, 14]. The direct discharge of toxic industrial wastes into the river system that ultimately reaches the beaches has drawn significant attention [13]. Several initiatives have been undertaken by government and private organizations but have not been enough to yield significant outcomes. Because these employ the conventional approach focusing on determining the water quality state, they have links with particular sectoral or sub-sectoral economic activities (e.g., textile industries and hotel businesses) [13–15]. However, the environmental performance of an economy is governed by all sectors, which are interrelated through supply chains. Analyzing the relationship between economic activity and water pollution is increasingly considered a useful approach to managing water resources [18, 19].

Generally, the pollution caused by economic activity is positively related to output. The economy of a country or region comprises several sectors, each of which receives inputs from its own and other sectors by delivering outputs. Analyzing the inter-sectoral relationships along with resource use (inputs) and pollutant emissions allows us to calculate resource use (e.g., energy, water, and land) and manage the environment (e.g., waste) [20]. Such an analysis identifies sectors as either pollution sellers, buyers, or both, which is essential for prioritizing pollution control policy [21]. To apply this approach, the conventional input–output (I–O) table is extended to include environmental parameters (e.g., water pollutant emission intensity), which are useful in evaluating the impact of production process (i.e., in the present or the future with changes in the economy) on the water environment [18, 22–24].

In this study, we employed the environmentally extended input–output (EEIO) model to tie water pollution together with Bali's economic activity. Broadly, our objective is to recommend policies for managing Bali's water pollution in context of its rising economy. The specific research objectives are to analyze the links between various economic activities and BOD emissions, estimate sectoral direct (as a source) and indirect (as a cause) BOD emission, classify sectors into comprehensive groups based on their BOD emission characteristics, and provide pollution control management strategies.

2 Study area

Bali, a province of Indonesia (Fig. 1), covers a total area of 5620 km^2, or 0.3% of the total land area of the Indonesian archipelago. The island lies entirely within the tropics and possesses a tropical marine climate. The average annual precipitation is approximately 17,411 mm [5]. Rivers, groundwater, and springs—the major freshwater resources—are not uniformly distributed across the region. Owing to the incidence of major rainfall (75–80%) during November through April, maintaining an adequate water supply for the agriculture and tourism sectors is a challenge during the dry season [25].

In 2018, the Balinese economy reportedly grew by 6.35%. The contribution of various sectors to the GRDP for 2018 is demonstrated in Fig. 2 [5]. The accommodation and food service sector's activities under tourism provide the dominant share of GRDP, followed by the agricultural, forestry, and fishery sector. The contribution of the agricultural, forestry and fishery sector has declined in recent years. The structure of Balinese economy has shifted from primary to tertiary economy with the recent growth of the tourism sector [5]. Other sectors, such as the transportation and construction industries, account for 9.5 and 9.4% of GRDP, respectively. These sectors have reported increasing growth in the GRDP owing to the expansion of the tourism sector. In total, 382 companies representing large (100 or more employees) and medium (20–99 employees) industries were in operation in Bali in 2017; of these, the food and beverage industry had the greatest share of the GRDP [5].

3 Materials and methods

3.1 Conventional I–O table

In an economy's production process, each sector requires inputs from its own and other sectors to produce goods and services. The concept of describing the interlinkages between sectors in an economic system was introduced by the economist Wassily Leontief. His I–O

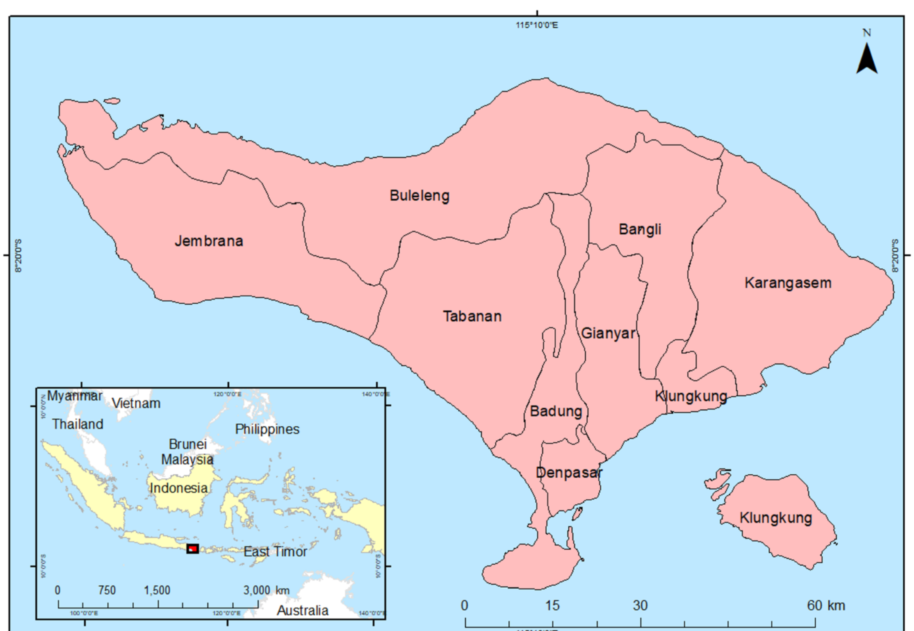

Fig. 1 Map depicting the location of Bali Province

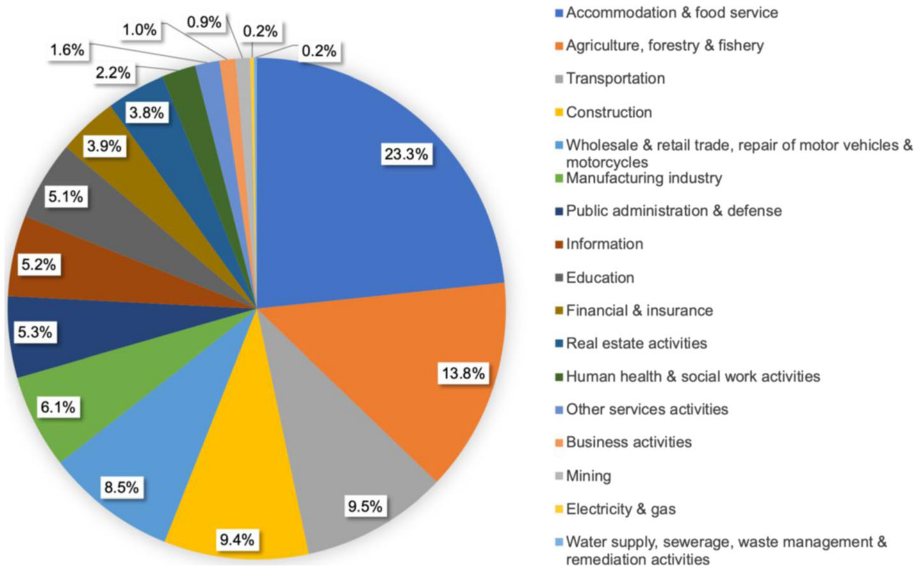

Fig. 2 Sectoral distribution of the gross regional domestic product (GRDP) of Bali, 2018

model is conventionally used to describe the interconnections between sectors [26]. Table 1 presents an example of an economy's flow of goods and services, visualizing the interdependence between the sectors. The rows represent the proportion of output that each sector sells (seller) to other sectors (purchaser); the columns represent the proportion of products and services required (purchased) by each sector from other sectors as inputs to meet total output. Apart from intermediate demand, an I–O table indicates the quantity of products and services consumed by households, the government, and exports (final demand) as well as the amount of products and services that sectors import (imports) and the compensation paid to labor (value added). I–O tables are formulated based on the data for a particular economic area, nation, or region [27].

Table 1 Schematic representation of a conventional I-O table

Sector	**Intermediate sector**					**Final demand**	**Total output**
(Buyer) j	***1***	**…**	***j***	**…**	***n***		
(Seller) i							
1	x_{11}	…	x_{1j}	…	x_{1n}	d_1	x_1
.	.	…		…			
.	.	…		…			
i	x_{i1}	…	x_{ij}	…	x_{in}	d_i	x_i
.	.	…		…			
.	.	…		…			
n	x_{n1}	…	x_{nj}	…	x_{nn}	d_n	x_n
Value added	v_1	…	V_j	…	v_n		
Import	m_1	…	m_j	…	m_n		
Total input	x_1	…	x_j	…	x_n		

An I–O table comprises a set of linear equations. The basic equation of Leontief's model describes the intersectoral relationships in an economic system [28]. It depicts the fact that total output is equal to the amount used internally used by the system as intermediate consumption plus the amount consumed by the final customers (Leontief as cited in Nguyen [18]).

$$x_i = \sum_{j=1}^{n} x_{ij} + d_i \tag{1}$$

where x_{ij} is intermediate consumption [18], d_i is the final demand for goods by each sector, and a_{ij} is the technical coefficients of production, which are described as the amount of products that the j^{th} sector purchases from the i^{th} sector to produce one unit of (j^{th}) output.

$$a_{ij} = \frac{x_{ij}}{x_j} \tag{2}$$

Eq. (1) can be rewritten as follows after incorporating a_{ij}:

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + d_i \tag{3}$$

Converting the equation into matrix notation for the entire economy yields the following:

$$\mathrm{x} = \mathrm{Ax} + \mathrm{d} \tag{4}$$

where A represents the $n \times n$ technical coefficient matrix with the element (Table 1).

Solving for x, we obtain the total production delivered to fulfill final demand as follows:

$$x = (I - A)^{-1} d \tag{5}$$

where I denotes an identity matrix and $(I - A)^{-1}$ is the Leontief inverse matrix. Let α_{ij} represent the elements of the Leontief matrix. Subsequently, the gross domestic output of sector i, x_i, can be expressed as follows:

$$x_i = \sum_{j=1}^{n} \alpha_{ij} d_i \tag{6}$$

3.2 EEIO model

I–O tables show the flows between sectors and frame their interrelationships. An EEIO analysis, an extension of Leontief's I–O model [27], is a simple and robust method for assessing the links between economic activity and environmental impact [29]. EEIO quantifies the environmental pressure along the supply chain while assuming an unchanged production structure [30].

The release of water pollutants is usually expected to be linearly proportional to the size of sectoral outputs [18]. We assume PI as pollution intensity and define it as the amount of water pollutants released to produce one unit of output (in monetary terms) for a sector. Its elements, PI_i^y, denote pollution intensity related to the y^{th} water quality parameter for sector i in a particular year. The $y \times n$ matrix, PI, is the pollution intensity matrix. The pollution load (PL) can then be computed using Eq. (7).

$$PL = PIx \tag{7}$$

The PL for the y^{th} parameter for sector i, PL_i^y, is expressed as follows:

$$PL_i^y = PI_i^y x_i \tag{8}$$

Substituting the value of x_i from Eq. (6) into Eq. (8) yields the following:

$$PL_i^y = PI_i^y \sum_j \alpha_{ij} d_i \tag{9}$$

The PL of sector i is the amount released to satisfy all production in this sector (x_i), including both the intermediate ($\sum_j a_{ij} x_j$) and final demand (d_i).

3.2.1 Water pollutant emissions

Each economic sector acts as both a supplier and receiver of inputs in the economy's production process. Based on their roles, the emissions of water pollutants from sectoral activities can be distinguished into two categories: direct (i.e., a source of emissions) and indirect (i.e., a cause of emissions). Direct emissions (DiE) are defined as the amount of water pollutants that are directly discharged by a sector in producing the products required to satisfy all forms of demand (i.e., intermediate demand and final demand) [19]. By contrast, indirect emissions (IDiE) are the amount of water pollutants that are discharged by a sector and other sectors to produce the inputs it requires. Unlike DiE, the amount of pollutants indirectly emitted by a sector relies heavily on the economic performance of several sectors. This form of pollution is not accounted for by the traditional method; however, pollution control management strategies have recently started incorporating examinations of IDiE [19].

Despite being good indicators, direct and indirect emissions still cannot express the flow of pollutants within a single sector [18, 19, 26]. These indicators cannot, for example, quantify the proportion of a sector's direct discharge that is required to meet its own sectoral demand (i.e., sectoral self-pollution) or the level of discharge equal to inter-sectoral demand. To overcome the inherent limitations of direct and indirect emission, we employed the vertical integrated coefficient method in sectoral pollutants analysis [26] and disaggregated the sectoral pollution loads into five components: (i) a sector's own pollution (OW_i^y) (the amount of y pollutant emitted by sector i to produce its own input); (ii) true forward pollution (TF_i^y) (the amount of y pollutant emitted by sector i to produce products used as inputs of others' intermediate demand); (iii) semi-own pollution (SOW_i^y) (the amount of y pollutant generated by sector i to produce the inputs for other sectors, which is required to produce inputs that sector i purchases to fulfill final demand); (iv) true backward pollution (TB_i^y) (the amount of y pollutant emitted by other sectors to provide inputs for a sector); and (v) final demand pollution (FD_i^y); (the amount of y pollutant directly emitted by sector i to produce products in fulfilling the final demand of a sector).

3.2.2 Data sources and EEIO preparation

Two datasets, namely, an I–O table and the sectoral water pollutant emission intensity, are required to perform EEIO modeling. We used a 2007 regional I–O table that originally consisted of 52 economic sectors. The I–O table was revised by removing the sectors that lacked relevant data (such as mining, basic metal industry and other metal goods industries) and merging the detailed economic sub-sectors into a major sector (e.g., agriculture, forestry and fishery). Finally, we developed a 16×16 sector I–O table to provide comprehensive results and overcome the limitation of lacking detailed pollutant emission intensities at the sub-sectoral level. The revised grouping of sectors is provided in Table S1 of Supplemental Materials.

The revised I–O table was further extended by adding the BOD emission intensity for each economic activity as a proxy indicator of overall water quality [31]. The intensity was defined as the amount of BOD (kg) discharged per unit of monetary output in millions of rupiah (IDR). The intensities were directly and indirectly collected/derived from various sources. The intensity for the manufacturing sector was obtained from a report on wastewater disposal for Denpasar [32]. The intensities were adjusted into 2007 prices (I–O table); price inflation was overcome through the consumer price index method. We derived the intensities for the selected sectors by calculating the BOD load in kg and taking its monetary output value in 2007. The pollutant load for Sector 1 (agriculture, forestry and fishery) was derived from the areas under each sub-sector [33] and the BOD export coefficients for major land use [34–36]. Similarly, the BOD load for Sector 2 (livestock and poultry) was calculated by taking daily livestock's load (BOD kg/d/cattle) [31] and slaughtering activities (kg/t of meat) [37] together with Bali's total number of cattle head and amount of meat produced in 2007 [33]. For hotels and restaurants, we took the total number of visitors and restaurant seats in 2007 [33] and calculated the BOD load per capita (visitor) per day and per restaurant seat [32]. In relation to the service sectors—namely, electricity and drinking water, trading, transport, communication, and financial institutions—that were not direct BOD emitters, the intensities from Nguyen et al. [18] were used to examine their role in indirect BOD emissions.

Table 2 presents the EEIO table developed for Bali. Sectoral outputs are expressed in millions of IDR; BOD emission intensity is expressed as kg per millions of IDR.

4 Results and discussion

4.1 Sources of and causes for BOD emissions

An estimated total of 246.9 kt of BOD was released in the economy's production process in 2007. Each sectoral direct BOD load is shown in Fig. 3. Three sectors—livestock and poultry (Sector 2); agriculture, forestry and fishery (Sector 1); and food, beverage, coffee and tobacco (Sector 4)—accounted for 99.5% of the total BOD emissions; of these, Sector 2 produced 96% of the total BOD emissions. The BOD amount varied among the sectors because of differences in BOD emission intensity and total output. The results are consistent with earlier findings that indicate livestock plays a major role in freshwater pollution in many parts of the world [31, 36]. The increasing population and the prevalence of many head of cattle—the reported increase in cattle and pig numbers was 3.62 and 11.73%, respectively, from 2017 to 2018 [5]—positioned this sector at the top in terms of water pollution. Conversely, the agricultural land under Sector 1 has recently been declining; however, the heavy use of fertilizers in intensive agricultural farming has kept the sector a leading cause of freshwater pollution. Followed by these two sectors, Sector 4 (food, beverage, coffee and tobacco) emitted BOD to a greater extent, with a value of 1.9 kt, which caters consumable goods for residents and tourist. This sector's role in water pollution has been notably increasing with increases of population and visitors in recent years.

The release of water pollutants increases with sectoral output, which is determined by a sector's intermediate and final demand. Intermediate demand reflects how heavily a sector engages in supplying its products to other sectors as inputs. Household consumption, government stock, and exports of a sectoral item determine a sector's final demand. Disaggregating the total PL as per the demand for each sector (Fig. 4) is an effective method of undertaking the appropriate policy measure in controlling water pollution. This figure illustrates that demand factors impact the BOD emissions differently for the various sectors. For instance, intermediate demand was the major cause of BOD emissions in four major sectors, including the top two BOD emitters (Sectors 1–3 and 12). This indicates that these sectors discharged major BOD in producing their products or services for other economic sectors. However, exports were the major cause of BOD emissions (more than 60% of BOD) in the sectors (Sectors 5–9 and 13) that mainly comprise manufacturing industries. This is likely attributable to Bali's adoption of an open economy as exports that plays an important role in the regional economy [5]. Household demand was the primary cause of BOD (nearly 50%) for Sector 4 (food, beverage, coffee and tobacco) and Sector 10 (electricity and drinking water), which are both heavily consumed by residents. Gross fixed capital had negative BOD values for Sectors 4 and 5, indicating that this portion (BOD) was not generated for that year but fulfilled by the stock.

Apart from the direct BOD discharge, we determined indirect BOD emissions by sector (Fig. 5). Sectors 2, 13, 1, and 4 produced as much BOD from other sectors or from themselves to satisfy their inputs. Sector 2 was the chief indirect BOD emitter, accounting for 65% of total BOD emissions; this is likely due to its reliance on its own sector, which is the top direct BOD emitter, for inputs (e.g., baby chicks, calves, fingerlings and animal feeds). Sector 13 (hotels and restaurants) is responsible for emitting 30% of total BOD owing to its close connection with other sectors—most likely the livestock and agricultural sectors, both major BOD emitters—to operate their business. Importantly, other service and trade sectors show a noticeable contribution to indirect BOD emissions as opposed to their role in direct BOD emissions. This is particularly essential for pollution control planning because the indirect emissions of these sectors are often overlooked.

Table 2 Extended I-O table

	Sector ID	Intermediate demand																Final demand			Total output
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	HH	GFC	Ex	
Economic sector (Million IDR)	1	490,069	70,629	–	1,605,659	62,833	1076	–	271,399	384	–	812	75	1297,237	–	–	2315	3,296,677	236,418	1,405,813	8,741,397
	2	12,230	2,551,914	–	25,849	–	–	–	–	252	–	–	–	1,403,216	–	–	78	2,696,820	101,999	170,948	6,963,305
	3	–	–	–	–	–	–	–	–	–	–	367,007	–	–	–	–	46	–	227	50,021	417,300
	4	14,136	268,643	–	75,661	781	–	–	1151	230	3	–	–	534,105	858	–	525	1,450,355	–248,937	785,353	2,882,865
	5	12,569	19	38	54	493,567	2103	–	2031	841	–	–	905	129,768	37,778	1297	55,724	542,996	−48,641	3,342,331	4,573,381
	6	1973	1370	4169	4260	230	151,887	–	–	2760	–	200,430	30,909	92,550	6688	55	2060	20,324	5531	1,534,663	2,059,858
	7	1071	83	38	115	981	1110	2713	2288	719	160	579	1177	5767	1225	2545	2940	41,113	67	88,951	153,640
	8	103,684	12,878	1825	955	79,155	18,902	3964	96,983	1896	429	21,923	58,726	15,157	1628	237	56,688	51,849	458	778,493	1305,829
	9	5553	101	29	263	7116	5137	45	2528	978	113	6397	16,164	5816	3897	548	5310	4906	3511	147,572	215,984
	10	1077	15,262	295	2104	116,302	11,182	7938	6422	5776	10,451	6834	17,432	288,250	17,679	33,791	39,622	647,805	–	–	1,228,222
	11	64,298	8140	46,643	1424	1260	4144	3	3009	71	2623	248,726	149,945	105,117	119,524	80,480	180,056	–	4,433,706	–	5,449,172
	12	199,339	688,772	2466	196,903	215,098	69,286	3270	86,122	4191	353	288,476	59,660	1,030,813	22,410	2036	51,660	2,374,230	12,830	1,603,081	6,910,996
	13	46,852	4042	230	13,444	70,675	2987	–	–	1416	6173	11,557	94,023	215,976	393,577	18,164	212,151	1,720,026	–	12,639,812	15,451,107
	14	62,144	207,974	2199	56,271	102,861	21,459	947	24,655	2477	8143	92,380	30,960	322,761	531,300	24,062	67,650	1,214,247	3627	4,708,397	7,484,513
	15	764	1103	5718	1142	48,776	9899	262	5838	292	653	14	95,058	64,985	25,062	35,799	52,683	254,666	–	832,194	1,434,908
	16	306,510	73,514	2865	22,560	165,616	54,270	9652	71,326	6768	26,688	178,052	802,718	450,100	286,000	24,783	464,159	2,563,134	4,276,203	2,699,610	12,484,528
BOD [kg (million IDR)$^{-1}$]		0.812	34.010	0.276	0.657	0.014	0.015	0.105	0.277	0.040	0.000	0.000	0.000	0.025	0.000	0.000	0.005				

Sector	Description		
1	Agriculture, forestry and fishery	11	Construction
2	Livestock and poultry	12	Trading
3	Padas stone and other minerals	13	Hotels and restaurants
4	Food, beverage, tobacco and coffee industries	14	Transportation, travel bureau and other transportation support services
5	Textile, apparel and leather goods industries	15	Communications, post and giro
6	Timber industry and wood products	16	Financial institutions and company services
7	Paper industry, paper and cardboard goods	HH	Household consumption
8	Fuels, chemical industry, rubber and plastics	GFC	Gross fixed capital formation
9	Other processing industries	Ex	Export
10	Electricity and drinking water		

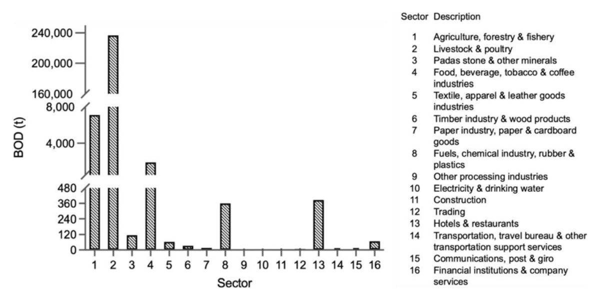

Fig. 3 Sectoral direct discharge of BOD in the 2007 Balinese economy

4.2 Disaggregation of sectoral BOD emissions

An analysis of the sectoral roles in indirect water pollutant emissions has added a new perspective to the conventional approach of direct sectoral water pollution. However, although these are good indicators, these aspects (i.e., direct and indirect pollution) remain unable to fully depict the behavior of sectoral pollution in the economy. To enrich our analysis, we demonstrate the flow of BOD throughout the entire economic sector (Table 3) and its various pollution components (Table 4). In Table 3, the rows of the matrix indicate the BOD amount that sector i produces to fulfill sector j's demand. The row sums represent the total BOD directly emitted by sector i in producing products or services to fulfill all forms of the economy's demand (i.e., *DiE*). The columns of matrix j indicate the purchases made by sector j from sector i during the production process, and the column sums represent the total BOD indirectly emitted by sector j from other sectors (i) in obtaining its input requirements (i.e., *IDiE*). The absence of row data for Sectors 10, 14, and 15 indicates that these sectors do not directly emit BOD (row), while the column values for the same sectors show their indirect role in producing BOD in the economy.

To further advance the sectoral pollution analysis, we disaggregate sectoral BOD loads into five components:

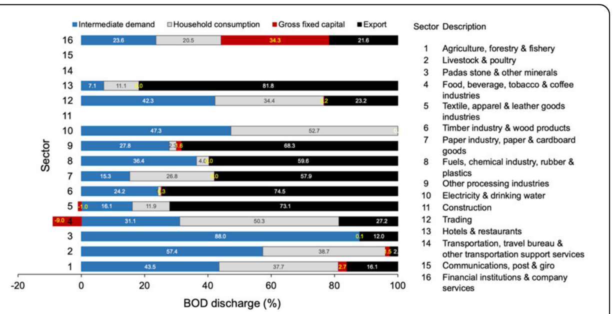

Fig. 4 Percentage of total BOD discharge attributable to each component of each sector's total output
Note: Sectors 11, 14 and 15 do not release significant BOD.

(i) a sector's own pollution (OW_i^y) (the amount of y pollutant emitted by sector i to produce its own input); (ii) semi-own pollution (SOW_i^y) (the amount of y pollutant generated by sector i to produce the inputs for other sectors, which is required to produce inputs that sector i purchases to fulfill final demand); (iii) true forward pollution (TF_i^y) (the amount of y pollutant emitted by sector i to produce products used as inputs in others' intermediate demand); (iv) true backward pollution (TB_i^y) (the amount of y pollutant emitted by other sectors to provide inputs for a sector); and (v) final demand pollution (FD_i^y); (the amount of y pollutant directly emitted by sector i to produce products in fulfilling the final demand of a sector) (Table 4).

The values vary among the sectors according to their different emission properties. For instance, a high value of TF_i^y for Sectors 1 and 2, pollution seller sectors, indicates that these sectors produce considerable BOD in satisfying intermediate demand. Similarly, Sector 2 is also responsible for producing substantial BOD (24.7% of the total BOD) in fulfilling its own inputs, highlighting the internal dependence of the sector (for their own inputs, i.e., OW_i^y). Other than Sectors 1, 2, and 3, a majority of sectors have a typically high range of TB_i^y, characterizing these sectors as pollution inducers that cause other sectors to emit BOD to fulfill their input needs. Among these, Sector 13 (hotels and restaurants) has an exceptionally high value, indicating a close linkage between this sector and others and its responsibility for producing a significant amount of the economy's water pollutants. Sector 4 (food, beverage, coffee and tobacco) is a major pollution inducer because of its processing of raw primary products (i.e., agricultural and livestock products) into edible food items.

4.3 Grouping of sectors

To distinguish the sectoral BOD emission behavior and appropriately identify the management plan, we grouped sectors by plotting the percentage of BOD—true forward pollution (TF_i^y)/direct emissions (*DiE*) and true backward pollution (TB_i^y) /indirect emissions (*IDiE*) (Fig. 6). *DiE* is defined as the amount of water pollutants (herein BOD) that are directly discharged by a sector while producing the products required to satisfy all forms of demand (i.e., intermediate demand and final demand) [19]. By contrast, *IDiE* is the amount of water pollutants (herein BOD) that are discharged by a sector and other sectors to produce the inputs that it requires. Generally, high TF_i^y /*DiE* values indicate that the sectors are liable to produce more water pollutants for other sectors, so the proportion of water pollutants produced for their own sectoral inputs is lower. Conversely, sectors with

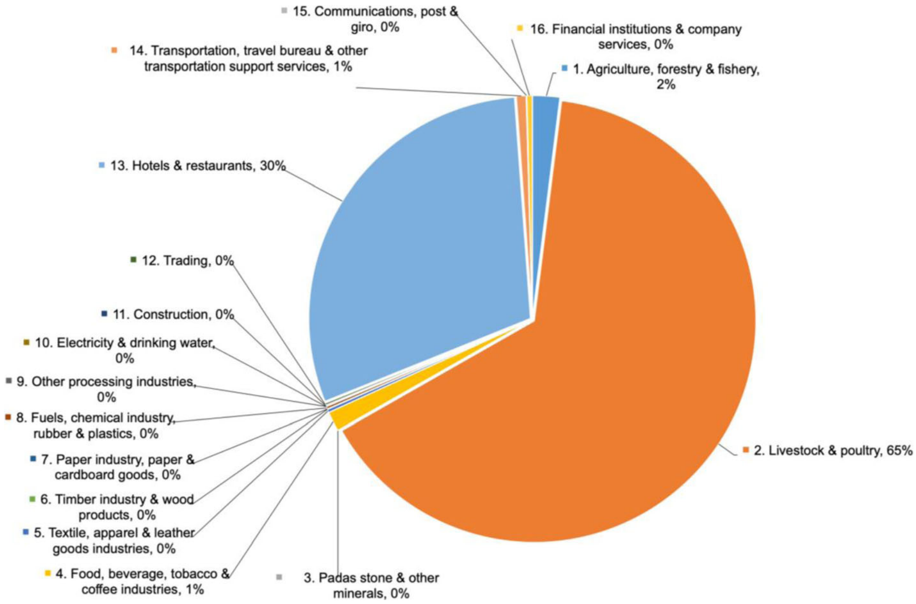

Fig. 5 Indirect BOD discharged by each sector relative to total BOD discharge in the Balinese economy, 2007

high TB_i^y /*IDiE* produce more water pollutants from other sectors.

Figure 6 shows that most sectors fall under Categories I and II. In contrast, there is only one sector in Category III, and none of the sectors belong to Category IV. Category I has less than 50% of both TF_i^y /*DiE* and TB_i^y /*IDiE*, indicating that these sectors depend heavily on their own sectoral input and produce more than 50% of the total direct and indirect sectoral BOD discharge in fulfilling their own sector's input demands. As major sources of pollution for their own input requirements, these sectors are characterized as self-polluting sectors. The pollution under this category could be better addressed by the product's final demand. In this regard, policy should focus on measures to lower household consumption and reduce the exports of these sectors.

Category II is similar to Category I in that TF_i^y /*DiE* < 50% but has a high TB_i^y /*IDiE* (i.e., more than 50%). In addition, by producing a large amount of BOD in fulfilling their own input requirements, these sectors indirectly produce a higher amount of BOD (more than 50% of the total sectoral indirect BOD emissions) from other sectors. Apart from self-polluters, these sectors are characterized as pollution inducers. Sectors such as Sectors 14 and 15 lie to the right bottom because of the lack of their own direct BOD discharge (*DiE* is 0); however, these sectors indirectly cause a significant amount of BOD from other sectors. In terms of the pollution control perspective, there is a need to examine input suppliers (seller sector) under this category and possible measures for switching the supplier sector from high- to low-polluting suppliers.

A single sector (Sector 3, i.e., padas stone and other minerals) is found under Category III. This possesses a high (over 50%) of TF_i^y /*DiE* but has a TB_i^y /*IDiE* value of less than 50%, indicating that the sector emits considerable BOD to fulfill intermediate demand and that it does not cause other sectors to produce BOD for its input requirements. In this case, it is best to consider pollutant reduction measures within the sectoral self-production process. Therefore, this category will be better dealt with by implementing in-house clean production technologies and wastewater treatment practices. No sectors can be found under Category IV, which is characterized by producing a huge amount of BOD indirectly from the other sectors (i.e., TB_i^y /IDiE > 50%) and also by producing a significant amount of BOD directly within the sector to fulfill other sectoral demands ($i.e., TF_i^y$ /DiE > 50%). The category demonstrates the dual characteristics of Category II (as pollution purchaser) and Category IV (as pollution seller), therefore, hybrid pollution control measures of those two categories are applicable in Category IV. Although we did not find any sectors in this category, two sectors (i.e., Sectors 10 and 12) were extremely close to this. This indicates that Sectors 10 and 12 produce huge amount of BOD to other sectors and equally liable to produce significant portion of BOD from other sectors.

5 Policy implications and perspectives for pollution control

The analysis herein of sectoral water pollution behavior in the production process of the economy offers vital

Table 3 Matrix of BOD (kg) flow in the economy

Sector ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	4,271,454	135,375	62	985,474	74,304	4529	712	162,217	759	433	7874	13,839	1,379,795	34,546	1725	28,450
2	581,348	159,642,177	488	1,189,520	409,448	28,480	1614	37,589	16,626	19,070	114,257	331,609	71,781,315	1,709,938	80,403	879,232
3	907	4444	13,977	323	303	128	6	131	6	35	87,253	1954	3278	2195	1249	2962
4	7103	122,916	3	1,343,289	2893	177	12	892	159	108	671	1891	398,284	9997	450	5197
5	144	30	0	42	59,693	34	1	37	10	2	30	57	2044	569	22	722
6	66	77	12	82	43	25,838	1	11	34	2	2936	375	1696	209	45	151
7	96	31	1	38	145	107	13,926	177	57	10	90	115	711	146	215	285
8	19,396	4691	79	5147	23,482	4904	1045	248,655	446	99	7601	11,268	17,246	1660	245	14,371
9	162	63	1	62	310	179	2	84	6292	3	276	404	451	162	23	199
10	1	3	0	1	22	2	1	1	1	123	2	3	56	5	5	7
1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
12	13	46	0	17	21	6	0	6	0	0	25	380	123	6	1	7
13	928	560	3	585	2051	142	8	112	34	97	577	1683	365,978	8714	410	4457
14	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
16	1165	684	4	469	1116	303	51	365	32	82	1103	2679	3937	1507	137	53,217

Sector	Description		
1	Agriculture, forestry and fishery	9	Other processing industries
2	Livestock and poultry	10	Electricity and drinking water
3	Padas stone and other minerals	11	Construction
4	Food, beverage, tobacco and coffee industries	12	Trading
5	Textile, apparel and leather goods industries	13	Hotels and restaurants
6	Timber industry and wood products	14	Transportation, travel bureau and other transportation support services
7	Paper industry, paper and cardboard goods	15	Communications, post and giro
8	Fuels, chemical industry, rubber and plastics	16	Financial institutions and company services

Table 4 Disaggregated sectoral pollution components with BOD loads (in tons)

Sector	Own pollution (OW_i^y)	Semi-own pollution (SOW_i^y)	True forward pollution (TF_i^y)	True backward pollution (TB_i^y)	Final demand pollution (FD_i^y)
1. Agriculture, forestry and fishery	240	23	2830	611	4012
2. Livestock and poultry	58,506	134	77,181	265	101,002
3. Padas stone and other minerals	–	0	101	1	14
4. Food, beverage, tobacco and coffee industries	35	3	551	2182	1305
5. Textile, apparel and leather goods industries	6	0	4	514	53
6. Timber industry and wood products	2	0	6	39	24
7. Paper industry, paper and cardboard goods	0	0	2	3	14
8. Fuels, chemical industry, rubber and plastics	18	0	112	202	230
9. Other processing industries	0	0	2	18	6
10. Electricity and drinking water	0	0	0	20	0
11. Construction	–	0	–	223	–
12. Trading	0	0	0	366	0
13. Hotels and restaurants	0	7	20	73,589	359
14. Transportation, travel bureau and other transportation support services	–	0	–	1770	–
15. Communications, post and giro	–	0	–	85	–
16. Financial institutions and company services	0	2	14	936	51

policy directives for controlling water pollution. In this study, livestock and poultry sectors were categorized as the chief BOD emitter; therefore, major attention should be paid to this sector. The handling and treatment of livestock waste is not common despite such waste containing valuable ingredients that can be processed for manure and biogas production. A typical BORDA biodigester of a satisfactory performance [17] is already in use in limited parts of Indonesia. By further improving the performance, the biodigester can be promoted as an effective method to control animal waste-derived water pollution. In relation to poultry waste, it is either composted or used for animal feedstuffs. Studies conducted globally and locally (i.e., in Indonesia) have demonstrated the possibility of turning poultry waste into valued feedstuffs for ruminants [38, 39]. Under the context of increased poultry waste, the policy of recovering animal waste and turning it into a valuable product would

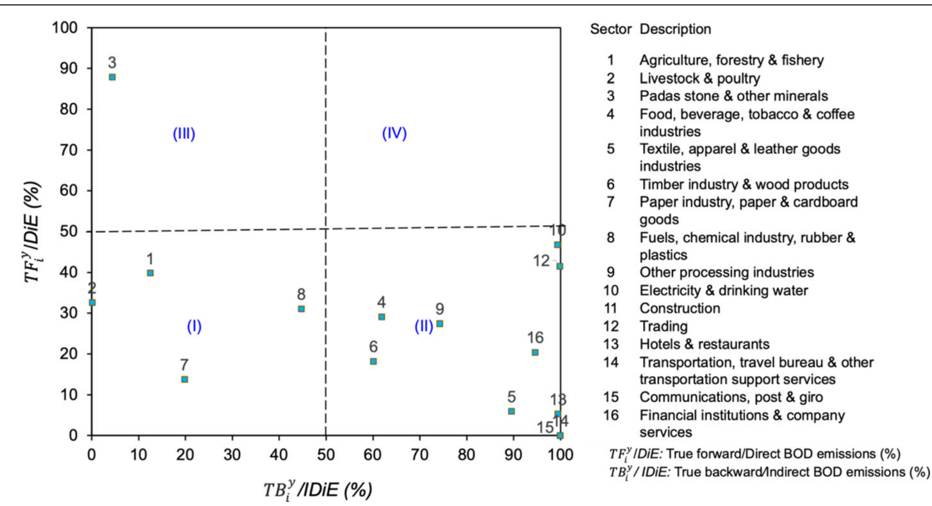

Fig. 6 Classification of sectors based on their BOD emissions characteristics

be the best option. Technical and financial issues in implementing related technologies should be supported by offering incentives. The application of the technologies (i.e., the biodigester or drying poultry manure for feedstuffs) would be more beneficial in terms of the technical and economic aspects for large-scale farming; therefore, policy encouraging the development of large-scale livestock and poultry farming should be prioritized. However, such change takes time and progress more gradually. To minimize the pollutant loads from agriculture, fertilizer usage, including doses, timing, and methods, should be considered. Cleaner production and wastewater treatment practices should focus on the safe discharge of the wastewater produced, especially from manufacturing industries such as Sectors 4 (food, beverage, coffee and tobacco) and 8 (fuels, chemical industry, rubber and plastics).

Decreasing the total output of each sector by cutting its demand is the best method to control water pollution. The total output consists of the intermediate and final demands of the economy, while the final demand is further directed by exports, households, and gross stock. These components of demand should be carefully examined and considered in terms of pollution reduction. For instance, exports are responsible for producing a significant amount of BOD from major manufacturing industries such as Sectors 5 (textile, apparel and leather goods), 6 (timber industry and wood products), 7 (paper industry, paper and cardboard goods), 8 (fuels, chemical industry, rubber and plastics), and 9 (other processing industries). Curtailing the exports of these sectors based on their pollution loads to minimize the water pollution load could be an alternative. However, such policies should be examined from an economic and social perspective to ensure the appropriate application, timing, and sustainable implication. Household consumption is the primary reason for BOD emissions by the top BOD emitters—Sectors 4 (food, beverage, coffee and tobacco) and 2 (livestock and poultry). Changes in household consumption, including changes in dietary habits (e.g., shifting consumable food items toward environmentally friendly products), could be the best approach to minimize the PLs from these sectors. Although such changes may take time, starting initiatives in this area would significantly impact pollution control in the long term. Considering indirect roles, Sector 13 (hotels and restaurants) demonstrates significant impact on water pollution by indirectly inducing BOD. The indirect BOD discharge of Sector 13 is around 190 times higher than the sector's direct BOD emissions. This sends an important message—aside from focusing on pollution control practices within the premises of hotels and restaurants, policy should also seek and prioritize supply-side pollution (from associated sectors). This provides new insights, such as offsetting the high investment cost for Sector 2 to adopt a wastewater treatment plant, by mobilizing the environmental fees/revenue collected from another sector, for example, the tourism sector. Alternatively, the possibility of decreasing the livestock and poultry population and increasing the imports of such products could be sought. Again, socioeconomic aspects should be evaluated for such decision-making.

The classification of the sectors (Fig. 6) serves as a useful tool in planning appropriate pollution control policies. Managing demand by lowering household consumption, changing food habits (toward environmentally friendly food), and curtailing exports are effective methods to inhibit the water pollution of the sectors in Category I. Sectors under Category II are subject to pollution control by seeking alternative input suppliers (from high- to low-polluting suppliers) aside from the measures suggested for Category I. Sectors under Category III will be better managed by implementing clean production technology and wastewater treatment practices.

6 Conclusions

This study is the first to analyze the relationship between economic activity and the potential for water pollution in Bali, Indonesia. Going beyond conventional methods, potential water-polluting sectors were identified in this study based on their direct and indirect roles in BOD emissions. This study recognizes significant BOD emission drivers, guiding policymakers and practitioners to target initiatives that reduce Bali's water pollution. Certain sectors—namely, Sector 2 (livestock and poultry), Sector 1 (agriculture, forestry and fishery), and Sector 4 (food and beverage)—accounted for 99.5% of the direct BOD discharge, among which Sector 2 accounted for 96% of the total BOD discharged. For direct BOD emissions, intermediate demand was a major driver in Sectors 1–3 and Sector 12. Similarly, exports were the cause of more than 60% of total BOD emissions for the manufacturing sectors (Sectors 5–9 and 13). Household demand dominated the major portion of BOD emissions in Sectors 4 (food, beverage, coffee and tobacco) and 10 (electricity and drinking water).

In particular, we determined each sector's indirect BOD emissions. The livestock and poultry sector, the top BOD emitter, produced more than 50% of its BOD for its own sector demand, which was also recognized as the most self-polluting sector. Hotels and restaurants heavily rely on other sectors and were responsible for indirectly emitting BOD from different sectors. Sectors such as the trades, transportation, and service sectors, whose direct BOD emissions are limited, still significantly contributed to indirect BOD emissions.

Moreover, we grouped the sectors into four categories. Those in Category I emit considerable water pollutants for their own input requirements; these sectors are called self-polluters and are better addressed by demand management and employing clean production technologies. Sectors in Category II directly emit a significant portion of water pollutants for their own sector's input demand but heavily rely upon the total indirect water pollutants from other sectors. This category's pollution control will be better managed by shifting from high- to low-polluting suppliers in addition to the measures employed in Category I. Category III emits water pollutants to fulfill other (intermediate) sectoral demand; therefore, clean production technology and wastewater treatment should be encouraged. No sectors fall under Category IV, which produces and causes more water pollutants for and from other sectors, and for which a hybrid of the measures suggest for Categories II and III should be employed.

7 Limitations

For this research, we used an available 2007 I–O table; however, using the latest I–O data would have enhanced our analysis. The estimated BOD levels may vary with the actual load but nonetheless, provide a clear trend and structural relationship between water pollution and economic activities, offering a good basis of pollution control in the rising Balinese economy. The pollution intensities of manufacturing industries are available for a limited industry. In the future, establishing pollution intensities for the subsectoral levels and adding new water quality indicators will further strengthen the analysis.

8 Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-021-00115-6.

Additional file 1: Table S1. Re-classification of sector for Bali Province.

Acknowledgments

The authors wish to thank the Ministry of the Environment of Japan (MoEJ) for funding the project and Badan Pusat Statistik Provinsi Bali (Statistics of Bali Province) for providing the necessary data.

Authors' contributions

SKC contributed to the conceptualization, methodology, data interpretation, reviewing, and writing—original draft preparation. GM contributed to the methodology and data interpretation. ABR assisted in the preparation of data and GIS map. CP processed the review and editing. IMS contributed to the policy implications. KF provided the supervision and funding acquisition. All authors read and approved the final manuscript.

Funding

This work was carried out as part of the United Nations University-Institute for the Advanced Study of Sustainability (UNU-IAS) project *Water for Sustainable Development (WSD)*, which is supported by the Ministry of the Environment of Japan (MoEJ).

Availability of data and materials

All data generated and analyzed during this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare they have no competing interests.

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Received: 7 June 2021 Accepted: 9 December 2021
Published online: 11 January 2022

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