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Estimation of greenhouse gas emissions: a case of Beur Municipal Wastewater Treatment Plant Unit-I, Patna, India

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ABSTRACT

Estimation of Greenhouse Gas (GHG) emissions from various activities of municipal wastewater treatment plant may suggest suitable action to reduce GHG emissions. Thus, in the present study a case of Beur Municipal Wastewater Treatment Plant Unit-I (BMWTP-I) having an installed capacity of 20,000 m^3/d has been considered for the estimation of carbon-based on-site as well as off-site GHG emissions. The study indicates that the BMWTP-I emits 18,038 and 7,115 kg $CO_{2\text{-eq}}$/d under not-flared and flared conditions, respectively. The off-site activity, which includes only the electricity consumption by the treatment plant, contributes as minimum as 20.55% under gas not-flared condition, and as maximum as 52.11% under gas-flared condition. Sludge digestion unit is identified as a major contributor of on-site GHG emissions with a share of 90.28 and 59.12% under gas not-flared and gas-flared condition. However in case of off-site emissions, only 3 out of 11 activities are responsible for 90.76% emissions. These activities are main pumping station, aeration tank and effluent lifting station whose individual contributions are 41.57, 34.64 and 14.55% respectively. Lower value of total GHG emission in the term of indicators such as per unit volume of wastewater treated, per kg BOD_5 removed and per capita per day have been observed under gas-flared condition compared to that under gas not-flared condition.

Keywords: Greenhouse Gas (GHG); Wastewater; On-site emission; Off-site emission; Global warming; Methane; Carbon dioxide

1. Introduction

Several human activities such as consumption of fossil fuel, rapid economic growth coupled with industrial and agricultural development, waste management etc are responsible for increased concentration of greenhouse gases (GHG) in atmosphere. These activities, in turn, are responsible for global warming and progressive climate change [1]. Environmentally hazardous GHG emissions from various activities are now receiving considerable attention worldwide to reduce the effect of climate change [2]. In year 2010, 48,629 MT $CO_{2\text{-eq}}$ GHG emissions were estimated worldwide, out of which approximately 3% was only from waste management related activities [3]. However in Indian scenario, GHG emissions from waste sector were 3.32% of the net GHG emissions [4],

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which is little more than the GHG emissions worldwide from waste management activities. GHG emissions from waste sectors mainly include emissions from municipal solid waste and wastewater originated from industrial as well as domestic/municipal activities. Literatures show, considerable efforts have been made to estimate GHG emissions from solid waste [5,6]. However, studies on estimation of GHG emissions from wastewater treatment plants located in developing countries like India is scanty. The Wastewater Treatment Plant (WTP) aims to remove oxygen demanding matters, pathogenic organisms, and other chemical contaminants present in the wastewater before the water can be discharged into water receiving bodies or reuse and recycle purposes [7]. However, literature reveals that WTPs also emit considerable quantity of GHG such as CO_2, CH_4, and N_2O into the environment [8]. In addition, GHG are also produced due to energy consumption at treatment plant, transportation of chemical for on-site usage, degradation of remaining constituents in effluents, transportation, and treatment of sludge and other associated activities. Thus, the wastewater treatment systems have been considered one of the larger minor sources of anthropogenic GHG emissions [9].

Keeping above points in view, a case of Beur Municipal Wastewater Treatment Plant (BMWTP) has been considered for the estimation of carbon based GHG emissions. BMWTP is one of the municipal wastewater treatment plants located on southern-west part of Patna, the capital city of Bihar state, at Beur (25°34′30.07′′N, 85°05′52.46′′E) under Patna Municipal Corporation (PMC) area. BMWTP has two units having installed capacity of 20 and 15 MLD designated as Unit I and Unit II respectively. Unit I is based on activated sludge process (ASP) having sludge digestion tank, sludge drying beds and gas flaring system. However, Unit II has facility only to provide primary treatment. Thus, Unit I has been considered as representative treatment plants of Patna for the estimation of GHG emissions and its flow diagram is presented in Fig. 1.

For the estimation of GHG emissions from wastewater treatment system, various methods have been proposed. Several organisations such as the Intergovernmental Panel on Climate Change (IPCC), World Resources Institute (WRI), and the US Environmental Protection Agency (US-EPA) have provided general guidelines for estimation of CH_4 and N_2O based on per capita waste load considering first order decay (FOD) kinetics. Bridle Consulting, (2007) has identified five distinguished activities in WTP where GHGs are emitted. They are biotreatment, sludge treatment, chemical usage, power consumption and biogas production [10]. Monteith et al. [11] suggested a rational procedure for estimation of GHG from municipal wastewater treatment plant. A comprehensive mathematical model was proposed by Shahabadi et al. [12,13] that estimates GHG emissions from a wastewater treatment plant of food processing industries. Detailed models that dynamically describe the behaviour of wastewater treatment plants have been developed by Ashrafi et al. [14].

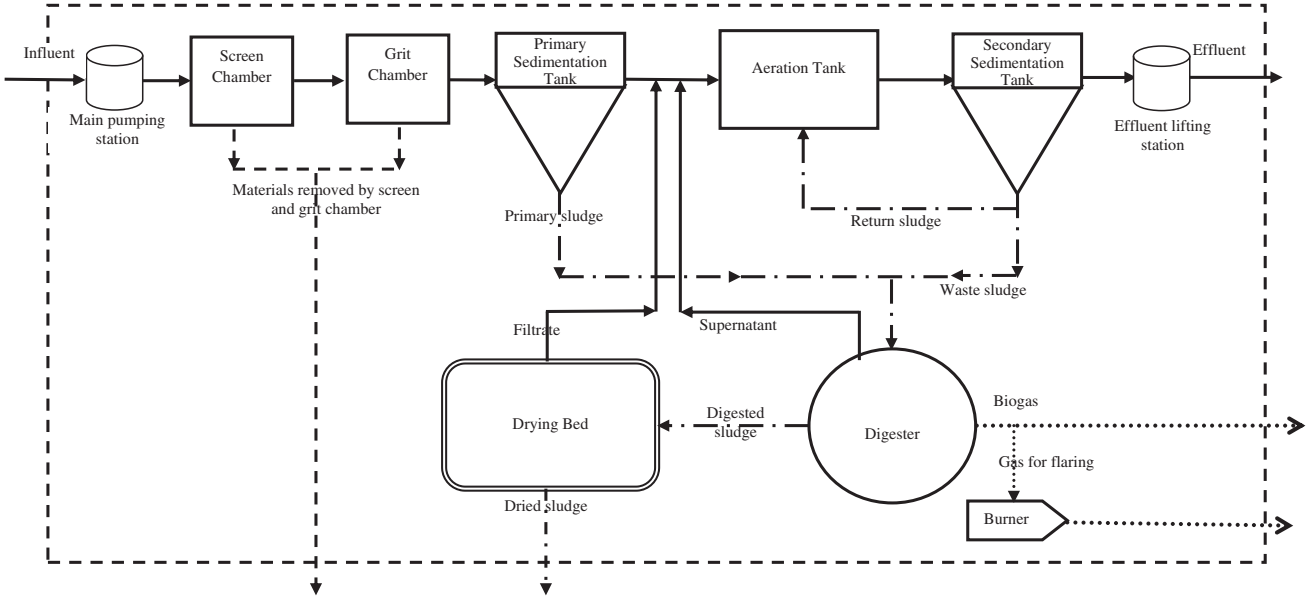

Fig. 1. Flow diagram of Beur Municipal Wastewater Treatment Plant Unit-I (BMWTP-I).

The guidelines proposed by IPCC, WRI and US-EPA provide regional inventories for GHG emissions. However, the remaining methods have been applied for well maintained and fully operational WTP with availability of most of the required data for estimation of GHG. The methodology applied for the well maintained and fully operational WTP may not be suitable because of poorly maintained, and lack of requisite records and data for the municipal wastewater treatment plant under consideration for the present study. In view of the above, it is necessary to consider and develop suitable modification in the existing methodology to suit a WTP such as the case study sample (Beur Municipal Wastewater Treatment Plant Unit-I "BMWTP-I") undertaken over here.

The present study aims to estimate on-site as well off-site carbon-based GHG emissions from the WTP under study, which are very common in developing and underdeveloped countries. The identification of major contributor of GHG emissions among various on-and off-site activities are also considered. An effort is also made to estimate GHG emission in terms of indicators such as "per unit volume of wastewater treated", "per kg of BOD_5 removed" and "per capita per day" by the BMWTP-I.

2. Methodology

The present study is emphasised on the on- and off-site CO_2 and CH_4 emissions only, from BMWTP-I. N_2O estimation has not been carried out because the system employed does not consider nitrification and denitrification. Further, the pathway of treated effluent discharge has not been considered in the study, though the IPCC 2006 method of GHG estimation does not consider CO_2 emission of the biogenic origin as a part of GHGs [15]. However various literatures reveal inclusion of CO_2 as GHG emission from the wastewater treatment plant as it emits during aerobic and anaerobic biodegradation in aeration tank (AT) of ASP and sludge digester, respectively [16–19]. Accordingly, the present study aiming to estimate overall carbon-based GHG emission from BMWTP-I also considers CO_2 emission as direct GHG emission.

On-site GHG emissions are due to physical and biological phenomena occurring in the course of wastewater treatment process in various units of BMWTP-I as well as sludge handling. The off-site GHG emissions are related to consumption of electricity by various electro-mechanical pumps and equipments in the plant causing GHG emissions at the place of electricity generation. The off-site GHG emissions are also due to transportation and disposal of dried sludge/solids. But, the present study is limited to only the electricity consumption in the plant.

The BMWTP-I consists of several units such as main wastewater pumping station, screen chamber (SC), grit chamber (GC), primary sedimentation tank (PST), AT, secondary sedimentation tank (SST), primary and secondary (return/waste sludge) sludge pumping stations, sludge digester, sludge drying beds, gas flaring system, filtrate pump and treated effluent lifting station.

2.1. On-site GHG emissions

For the estimation of on-site GHG emissions, the amount of biodegradable matters generated/removed due to physical process as well as bio-degradation has been carried out for each unit operation and/or process employed in BMWTP-I.

2.2. Estimation of biodegradable matters generated/removed in various units

The units namely SC and GC are employed as preliminary treatments for the removal of floating matters (sticks, rags, plastics, papers, eggs, cells, etc), and inorganic solids (pebbles, sand, silt, glass, metal etc), respectively [20]. Materials removed by screen and GC are directly disposed on land. Since these matters are inorganic in nature, GHG emission is not expected.

2.2.1. Biodegradable matters from PST

The purpose of PST is to concentrate and remove settleable/suspended inorganic/organic solids through discrete settling without involving any biochemical reaction. Thus, the possibility of on-site GHG emission is negligible. However, the concentrated settleable organic solids are the potential source of GHG emission as it undergoes anaerobic digestion in sludge digester. In BMWTP-I, the solids are being removed from PST and pumped to the anaerobic digester for further digestion and volume reduction. The PST effluent gravitates to AT. The quantity of solids removed by the PST is determined employing Eq. (1) [20]:

$$M_{pst} = Q\,TSS_i\,P_{TSSR} \quad (1)$$

where M_{pst} = primary sludge, kg/d; Q = wastewater flow rate, m^3/d; TSS_i = influent total suspended solids, g/m^3; P_{TSSR} = TSS removal efficiency in PST, %.

2.2.2. Biodegradable matters from SST

ASP consists of AT where incoming organic solids (BOD_5) are contacted with return sludge to maintain adequate biomass in the presence of oxygen and SST in which bio-flocs settle down. It is assumed that all bio-chemical reactions take place in AT only and SST acts as solids separation facility unit. A portion of incoming organic solids (BOD_5) to AT gets oxidised and remaining portion is converted to new cell or active biomass (VSS). Therefore, the amount of organic solids oxidised and converted to new cells is required to be determined.

The BMWTP-I lacks in proper and reliable records and data keeping related to plant monitoring and performance. The data available for the BMWTP-I are the design parameters and sizes of various unit operations and processes (Table 1). AT is designed for MLSS (i.e. X) of 2,500 mg/L and Food by Micro-organism (F/M) ratio of 0.2. Considering the above design parameters, a mass balance equation has been worked out for AT with completely mixed steady state condition to know the volume of Return Sludge (Q_r). This, in turn, will provide information regarding amount of organic solids utilised for the said purposes. The diagram for mass balance across ASP (AT + SST) is given in Fig. 2, other parameters such as Y (biomass yield coefficient) and endogenous decay coefficient (k_d) have been suitably taken from the literature to match the steady state condition parameters (Table 1). The BOD_5 utilised in AT is the sum of BOD_5 converted to active biomass and BOD_5 oxidised. BOD_5 oxidation provides energy to active biomass cell during log growth phase, as well as responsible for endogenous respiration. The TSS coming from PST to AT constitutes volatile as well as non-volatile portion. The volatile portion is taken care of in BOD_5, which undergoes aerobic/anaerobic process and is responsible for GHG emission. However, non-volatile portion does not exert BOD_5 and contributes no GHG emission. As a consequence, it is, not considered in mass balance.

Mass balance across AT is given in Eq. (2), VSS inflow + biomass yield = VSS outflow:

$$Q\,X_{pst} + Q_r\,X_r + Y\,(S_{pst} - S_{es})Q = (Q + Q_r)\,X \tag{2}$$

where X_{pst} = effluent volatile suspended solids of PST, g/m^3; Q_r = return sludge flow rate, m^3/d; X_r = VSS concentration in return sludge, g/m^3; Y = Biomass yield coefficient, g VSS/g BOD_5; S_{pst} = Effluent BOD_5 of PST, g/m^3; S_{es} = Effluent soluble BOD_5 of SST, g/m^3; X = Mixed liquor suspended solids in AT, g/m^3.

Though the SST is designed to separate and concentrate the solids (active biomass), some parts of the solids escape the system along with effluent. Further, a portion of settled solids is returned to AT as return sludge (Q_r) to have adequate biomass to maintain desired level of F/M ratio and remaining portion of settled solids is removed as waste secondary sludge

Table 1
Plant parameters of BMWTP-I

Parameter	Value	Refs.
Wastewater flow rate (Q), m^3/d	20,000	Design parameter
Influent BOD_5 (S_i), g/m^3	150	,,
Influent TSS (TSS_i), g/m^3	300	,,
Effluent BOD_5 Total (S_e), g/m^3	30	,,
Effluent TSS (TSS_e), g/m^3	50	,,
Food to micro-organism ratio, (F/M)	0.2	,,
MLSS in aeration tank (X), g/m^3	2,500	,,
Return active biomass concentration (X_r), g/m^3	8,000	,,
BOD_5 removal in PST (P_{SR}), %	30	,,
TSS removal in PST (P_{TSSR}), %	60	,,
Volume of aeration tank (V_{AT}), m^3	3,637.50	,,
VSS/TSS in primary sludge	0.5	Suitably assumed
Effluent soluble BOD_5 (S_{eS}), g/m^3	5.75	,,
Effluent VSS (X_e), g/m^3	25	,,
Biomass yield (Y), (g VSS/kg BOD_5 removed)	0.68	[21]
Endogenous decay coefficient (k_d), d^{-1}	0.05	,,
VSS/TSS in secondary sludge ($SS_{R\text{-}VSS/SS}$)	0.85	,,
VSS reduction in digester, %	50	[22]
Biogas produced per kg VSS destroyed, m^3/kg VSS destroyed	0.9	,,

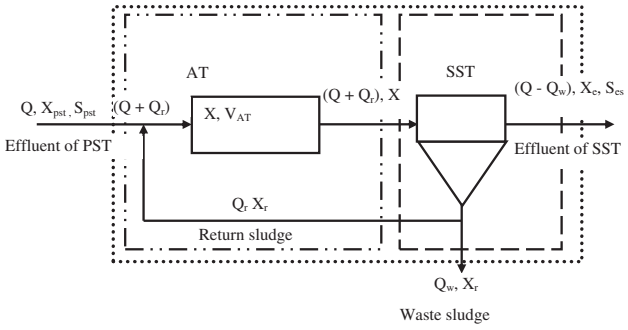

Fig. 2. Mass balance around AT and SST.

(Q_w), which is pumped to sludge digester. Mass balance of solids over the SST has been worked out and given in Eq. (3) to determine waste secondary sludge ($M_w = Q_w X_r$).

$$(Q + Q_r) X = (Q - Q_w) X_e + Q_r X_r + Q_w X_r \quad (3)$$

where Q_w = Flow rate of waste secondary sludge, m^3/d; X_e = VSS concentration in final effluent, g/m^3; M_w = Mass of waste secondary sludge, g/d.

2.2.3. Biodegradable matters oxidised during endogenous respiration

Solids retention time (SRT) is determined employing Eq. (4):

$$SRT = [V_{AT} X]/[Q_w X_r + (Q - Q_w) X_e] \quad (4)$$

where V_{AT} = volume of AT (m^3).

The amount of biomass decayed in one day in AT due to endogenous respiration has been determined using Eq. (5):

$$M_{decay} = V_{AT} k_d X \quad (5)$$

where M_{decay} = mass of biomass decayed in AT, g/d; k_d = endogenous decay coefficient, d^{-1}.

2.2.4. Volatile solids entering the digester

The sludge digester receives solids namely primary sludge from PST (M_{pst}) as well as waste secondary sludge from SST (M_w), which is expressed in Eq. (6):

$$M_d = M_{pst} + M_w \quad (6)$$

where M_d = mass of solids received in digester, g/d; M_{pst} = mass of solids (primary sludge) removed from PST, g/d; M_w = mass of solids wasted (waste secondary sludge) from SST, g/d.

The quantity of volatile solids (VS) entering the digester per day, $M_{d\text{-}VSS}$ is expressed in Eq. (7):

$$M_{d-VS} = (VSS/TSS)_{ps} M_{pst} + (VSS/TSS)_{ws} M_w \quad (7)$$

where $M_{d\text{-}VS}$ = mass of VS entering to digester, g/d; $(VSS/TSS)_{ps}$ = ratio of volatile and total suspended solids in primary sludge; $(VSS/TSS)_{ws}$ = ratio of volatile and total suspended solids in waste secondary sludge.

A portion of VS gets destroyed and converted into biogas and rest of the portion of VS remains in digester. The mass of VS destroyed per day, $M_{d\text{-}VS\ d}$ is given in Eq. (8):

$$M_{d-VS\,d} = P_{VS-d} M_{d-VS} \quad (8)$$

where $M_{d\text{-}VS\ d}$ = mass of VS destroyed, g/d; $P_{VS\text{-}d}$ = mass fraction of VS destroyed in digester (%).

2.3. Estimation of on-site CO_2 emission due to aerobic process

In the AT, the micro-organism acts on organic matter and converts into CO_2 and H_2O, as well as *in-situ* new cells are created and old cells get decayed in endogenous respiration process resulting in the emission of CO_2. The organic matter and biomass are represented by the chemical formula $C_{10}H_{19}O_3N$ and $C_5H_7O_2N$, respectively [23]. Estimation of CO_2 is carried out based on aforesaid biological activities and it is described in the Eqs. (9) and (10):

$$2\,C_{10}H_{19}O_3N + 25\,O_2 = 20\,CO_2 + 16\,H_2O + 2\,NH_3 \quad (9)$$

$$C_5H_7O_2\,N + 5\,O_2 = 5\,CO_2 + 2\,H_2O + NH_3 \quad (10)$$

Eq. (9) depicts that for each kg of BOD oxidised, 1.1 kg CO_2 is emitted. In case of endogenous respiration (Eq. (10)), for each kg of biomass decayed 1.42 kg O_2 is required and 1.947 kg CO_2 is emitted.

Keeping above in view GHG emission expressed kg $CO_{2\text{-}eq}$ per day (kg $CO_{2\text{-}eq}$/d) emission has been estimated with variation of various wastewater and operating parameters such as influent BOD_5, BOD_5 removal efficiency, F/M ratio, biomass in AT, SRT etc using Microsoft Excel spread sheet.

2.4. Estimation of on-site CO_2 and CH_4 emission from anaerobic digestion of solids

The volume of biogas produced per day, V_{BG} is determined employing method suggested by Monteith et al. [11] as given in Eq. (11):

$$V_{BG} = BG_{pr} M_{d-VS\,d} \quad (11)$$

where V_{BG} = volume of biogas produced, m^3/d; BG_{pr} = biogas production rate (m^3 gas/kg VS destroyed).

Biogas contains both CH_4 and CO_2 along with other gases. For the determination of mass production rate per day for each gas, Eq. (12) has been used:

$$G_i = VF_i\, V_{BG}\, MW_i\, P/RT \quad (12)$$

where G_i = mass of gas i produced, g/d; VF_i = volumetric fraction of gas i in biogas; MW_i = molecular weight of gas i, g/mole; P = pressure of biogas, atm; R = gas constant (8.21×10^{-5} atm-m^3/mole-K); T = standard temperature in °K.

Quantification of on-site GHG emission from sludge digester has been done with two conditions namely non-flaring of gas and flaring of gas. The gas flaring system consists of piping with gas burner to flare the gas without any pre-treatment. Since the flaring system is installed very close to the sludge digester and considering cent per cent burning of biogas, no leakage has been considered.

2.4.1. Quantification of on-site GHG emissions under non-flaring condition

This is expressed as $CO_{2\text{-eq}}$ and is calculated employing Eq. (13) as given below:

$$G_{CO_{2-eq}} = \sum G_{CO_2} + GWP_{CH_4} \sum G_{CH_4} \quad (13)$$

where $G_{CO_{2-eq}}$ = mass of $CO_{2\text{-eq}}$ produced, kg/d; G_{CO_2} = mass of CO_2 produced, kg/d; GWP_{CH_4} = global warming potential of CH_4; G_{CH_4} = mass of CH_4 produced, kg/d.

2.4.2. Quantification of on-site GHG emissions under gas flaring system

The biogas generated from the anaerobic digester consists of mainly CH_4 and CO_2. During the flaring of the biogas, CH_4 gets converted into CO_2 and this is represented by the following chemical equation:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \quad (14)$$

Thus, upon flaring one kg CH_4 is converted into 2.75 kg CO_2. Considering cent per cent conversion of CH_4 into CO_2, the total GHG emission has been estimated employing Eq. (15):

$$G_{CO_{2-eq}} = \sum G_{CO_2} + 2.75 \sum G_{CH_4} \quad (15)$$

2.5. Off-site GHG emission due to energy consumption

Off-site GHG emission has been determined by multiplying emission factor calculated for Indian power generation for the year 2014 and total energy consumption for the operation of pumps and other electro-mechanical equipments per day in the said plant. Emission factor has been determined employing Eq. (16) [12]:

$$EF = \sum PS_i\, EF_i \quad (16)$$

where EF = emission factor for Indian power generation; PSi = per cent share of ith mode of power generation; EFi = emission factor for ith mode of power generation.

3. Results and discussion

Based on aforesaid adopted methodology, the GHG estimation from BMWTP-I employing conventional ASP with anaerobic digestion and gas flaring system has been carried out using Microsoft Office Excel 2007. The on-site GHG emissions resulting from biodegradation of organic matters in the AT and sludge digester and off-site GHG emission on account of energy consumption on the plant has been computed. The effect of plant operational data on GHG emission has also been studied. The results of the aforesaid study are as under.

3.1. On-site GHG emissions

In BMWTP-I, the primary and waste secondary sludge are collected and decomposed in anaerobic environment in a suitably designed digester for further digestion and volume reduction. Quantity of primary sludge has been determined employing (Eq. (1)), and it comes to 3,600 kg/d. Quantity of primary sludge is directly proportional to wastewater flow, inlet TSS and primary clarified efficiency, however the amount of GHG emission from primary

sludge is dependent on VSS available in the sludge. More the VSS in the sludge more is the GHG emission potential as it undergoes biodegradation in digester resulting in CH_4 emission. The quantity of waste secondary sludge depends on the quantity of biomass coming from AT to the SST, quantity of biomass escaping from the system with effluent and the quantity of biomass returning to the AT as return sludge. Quantity of waste sludge could only be determined if quantity of return sludge is known. A mass balance is established around AT at steady-state condition for the given concentration of biomass in AT at a design value of F/M ratio of 0.2 to determine the value of return sludge. As the available plant data are not adequate for the determination of return sludge as well as waste sludge, hence the same along with other necessary parameters are suitably assumed based on information available in literature presented in Table 1. Considering above steps, the amount of waste sludge is determined and it comes to 852.46 kg/d. Besides these, other estimated parameters such as efficiency, hydraulic detention and solids retention, BOD_5 removed at various stages etc are calculated and presented in Table 2.

Anaerobic digestion of primary and waste sludge produces biogas, which contains GHG gases namely CH_4 and CO_2 along with other gases. A total 1,136.00 m^3/d biogas production is estimated, which is the sum of 810.00 and 326.00 m^3/d contributed due to anaerobic digestion of primary and waste sludge, respectively (Table 2). Though the quantity of waste sludge is 23.67% of the primary sludge but its biogas production potential is 40.26% of the primary sludge. The biogas production potential of waste sludge is 0.38 m^3 per kg sludge, whereas for primary sludge it is only 0.23 m^3 per kg sludge. Thus, the biogas production potential of waste sludge is 1.70 times more than that of primary sludge. The reason for greater biogas production potential per kg of waste sludge in comparison to that of primary sludge is due to higher content of VSS (85%) in the waste sludge. Biogas contains two major GHGs namely CH_4 and CO_2 with volumetric fraction of 0.65 and 0.32, respectively [22]. Thus, biogas produced in the digester contributes 491 kg CH_4 and 665 kg CO_2 in one day operation (Table 3). The above discussion depicts that managing of relatively small quantity of waste sludge will result in larger reduction in GHG emission in comparison to that for primary sludge.

Two activities namely growth of biomass in activated growth phases and decay of cells in endogenous phase occurs in AT. During these process only CO_2 as GHG is emitted, which can be estimated employing Eqs. (9) and (10). Table 4 shows that the amount of CO_2 generated during growth phase and endogenous phase are 427 and 966 kg/d, respectively. This indicates that the GHG emission during endogenous phase is more than twice that for growth phase of aerobic process in AT. However, the sludge digestion process contributes 90.28 and 59.12% of the total

Table 2
Estimated parameters of BMWTP-I

Parameters	Value
BOD_5 removal efficiency (%)	80.00
Hydraulic detention time (θ), hr	4.37
Solids retention time (SRT), d	7.35
Volume of return sludge, m^3/d	10,092.98
BOD_5 removed by BMWTP-I, kg/d	2,400.00
BOD_5 removed by PST, kg/d	900.00
Sludge produced by PST, kg/d	3,600.00
BOD_5 removed by waste secondary sludge, kg/d	702.86
Waste sludge from SST, kg/d	852.46
BOD_5 removed by endogenous respiration, kg/d	409.16
BOD_5 removed due to growth phase/provide energy, kg/d	388.00
Biogas production due to anaerobic digestion of primary sludge (m^3/d)	810.00
Biogas production due to anaerobic digestion of waste sludge (m^3/d)	326.00
Total biogas production in digester (m^3/d)	1,136.00

Table 3
Parameters pertaining to estimation of GHG in biogas from the digester

Parameter	CH_4	CO_2	Refs.
Volumetric fraction of gas (m^3)	0.65	0.32	[18]
Molecular weight of gas i (g/mol)	16	44	[15]
Gas constant (8.21×10^{-5} atm m^3/mol K)	0.0000821		[11]
Pressure of biogas (atm)	1		Standard pressure and temperature
Biogas temperature (°K)	293.15		
$G_i = VF_i\ V_{BG}\ MW_i\ P/RT$ (kg/d)	491	665	Calculated in the present study

Table 4
On-site activity wise GHG emission under biogas not-flared and flared conditions

Unit		GHG emissions (kg/d)		Not-flared condition(kg/d)		Flared condition (kg/d)	
		CO_2	CH_4	$CO_{2\text{-eq}}$	% Emissions	$CO_{2\text{-eq}}$	% Emissions
Aeration tank	Growth phase	427	–	427	2.98	427	12.53
	Endogenous phase	966	–	966	6.74	966	28.35
Sludge digestion		665	491	12,937	90.28	2,015	59.12
Total		2,058	491	14,330	100.00	3,408	100

on-site GHG emission under not-flaring and flaring condition, respectively. Table 4 indicates that the total on-site CO_2 and CH_4 emission are 2,058 and 491 kg/d, respectively. Under the flaring condition the CH_4 gets converted into CO_2 and H_2O. Upon flaring of gas, one kg CH_4 produces 2.75 kg CO_2 as described in Eq. (14). Considering Global Warming Potential of CH_4 (GWP_{CH4}) 25 times higher than the CO_2 on 100-year period [24], the total GHG emission in terms of kg $CO_{2\text{-eq}}$ per day under non-flaring and flaring conditions are 14,330 and 3,408 respectively. This is due to the fact that flaring of one kg CH_4 results in the reduction in GWP from 25 CO_2 units to 2.75 CO_2 units as computed from the Eq. (15).

It is evident from the Table 4 that the total GHG emission has reduced from 14,330 kg $CO_{2\text{-eq}}$ per day to 3,408 kg $CO_{2\text{-eq}}$ per day by flaring of gas. This results in reduction in 76.22% GHG emission due to flaring of the gas. It is due to the fact that anaerobic sludge digestion emits CH_4 which has GWP of 25 times higher than the CO_2 [24].

Further it is observed that anaerobic sludge digestion contributes major share of $CO_{2\text{-eq}}$ emission i.e. 90.28 and 59.12% under not-flared and flared conditions and the remaining are due to the activities occurring in AT. Hence, in the conventional wastewater treatment plant with sludge digestion, the major contributor of GHG emission is anaerobic activity in sludge digestion system. The BMWTP-I has no provision for gas utilisation either for waste to energy system or using gas as cooking gas in the nearby area. This provision will further attribute reduction in GHG emission from the plant. The GHG emission in terms kg $CO_{2\text{-eq}}/m^3$ wastewater treated is estimated as 0.72 and 0.17 without and with gas flaring system, respectively (Table 5). Monteith et al. [11] has observed $CO_{2\text{-eq}}$ produced per m^3 wastewater treated in the range of 0.153–0.28 kg for conventional ASP with the provision of gas flaring system. The GHG emission estimated in the present study is in agreement with Monteith et al. [11] observations.

Alternatively, the GHG emissions per kg of BOD_5 removal by the plant are also estimated to 5.97 and 1.42 kg $CO_{2\text{-eq}}$/kg BOD_5 under the condition when gas is not flared and gas is flared, respectively (Table 5). Keller and Hartley [25] reported total GHG emissions of 2.4 and 1.0 kg $CO_{2\text{-eq}}$/kg COD removed for fully aerobic and anaerobic process based wastewater treatment plants, respectively. Considering COD of municipal wastewater 2.4 times greater than BOD_u and BOD_5/BOD_u ratio of 0.68, the corresponding value calculated to 3.68 Kg CO_{2eq}/kg BOD_5 removed. The conversion from kg $CO_{2\text{-eq}}$ emission/kg COD removed to kg $CO_{2\text{-eq}}$ emission/kg BOD_5 removed was carried out employing Eq. (17) suggested by Shahabadi et al. [12]:

$$(2.4\,\text{Kg}\,CO_{2-eq}/\text{kg}\,\text{COD}) \times (2.4\,\text{kg}\,\text{COD}/\text{kg}\,BOD_u) \times (\text{kg}\,BOD_u/0.68\,\text{kg}\,BOD_5) = 3.68\,\text{kg}\,CO_{2-eq}/\text{kg}\,BOD_5 \quad (17)$$

Table 5
Comparison of On-site total GHG emission under gas not-flared and flared conditions

Particulars	GHG emission	
	Not-flared condition	Flared condition
GHG emission, kg $CO_{2\text{-eq}}$ per m^3 per wastewater treated	0.72	0.17
GHG emission, kg $CO_{2\text{-eq}}$ per kg BOD_5 removed	5.97	1.42
GHG emission, kg $CO_{2\text{-eq}}$ per capita per day	0.16	0.04

In a similar study, the overall GHG emissions of 1,952 kg $CO_{2\text{-eq}}$ were reported while treating 2,000 kg BOD_u in a day employing aerobic treatment process. The corresponding value in terms of kg $CO_{2\text{-eq}}$/kg BOD_5 is 1.44, which is very close to the estimated $CO_{2\text{-eq}}$ emission under gas-flared condition of the present study.

The most common practice to express GHG emissions from wastewater treatment plants are either as kg $CO_{2\text{-eq}}$ per m^3 wastewater treated or as kg $CO_{2\text{-eq}}$ per kg BOD_5 removed. However, the size of cities or municipal areas is generally expressed in terms of how many people live in that area. Therefore, it will be better if GHG emissions could also be linked with the population staying in that particular area and expressed in kg $CO_{2\text{-eq}}$/capita-day. Since the catchment area of BMWTP-I do not have any water bearing industrial units, hence the wastewater reaching to the plant is only human sewage and accordingly the population catered by the plant has been considered for computation of GHG emission in terms of per capita per day. Owing to the fact that the BMWTP-I has installed capacity to treat 20,000 m^3 per day and wastewater generation is 0.8 times the portable water supplied to the city. The standard rate of portable water supply for Indian cities is 135 L per capita per day [26]. Following the above steps, per capita GHG emissions for Patna municipal area comes to 0.16 and 0.04 kg $CO_{2\text{-eq}}$ under gas not-flared and flared conditions, respectively (Table 5). This indicates reduction of 75% in GHG emission by flaring the gas generated from BMWTP-I.

3.2. Off-site GHG emission

Though off-site emission from BMWTP-I is also associated with degradation of biodegradable remains in effluent wastewater, transportation and degradation of digested sludge, however, in the present study, only emissions due to electricity consumption in the plant is considered. A total of 11 locations in the plant are identified, where motors/pumps have been installed (Table 6).

Total energy consumption for a single day operation is estimated to 6,460.36 kWh, which accounts for 0.33 kWh/m^3 wastewater treated. The estimated energy consumption rate for BMWTP-I is almost 65% higher than the electricity consumption reported (kWh/m^3) by Shahabadi et al. [12], whereas Sahely et al. [27] have observed lower electricity consumption (0.2 kWh/m^3). Wei et al. [28] have estimated 0.49 kWh/m^3 of the treated wastewater from locomotive repair factory in China.

The installed and operational capacities of pumps/motors and their average operating duration are presented in Table 6. The installed capacity especially for main pumping station and effluent lifting station include the standby provisions. The operational capacities are maximum capacities on which plant operates during peak period.

From Table 6, it is evident that mainly three locations namely main pumping station, AT and effluent lifting station account for 41.57, 34.64 and 14.55%, respectively, totalling to 90.76% of total electric energy requirement. So there is a need to optimise the equipment used for the above said activities in order to reduce energy consumption.

The energy supplied to the BMWTP-I comes from the national grid which is fed by several power generating stations installed across India. All India installed capacity of power generating stations as on 31 January 2015 has been taken from Central Electricity Authority Report January 2015 [29]; and the same is presented in Table 7.

Table 6
Electricity consumption in BMWTP-I

Electricity consumption unit	Installed capacity (HP)	Operational capacity (kW)	Duration (h/d)	Energy consumption (kWh/d)	% Energy consumption
Main pumping station	275	111.9	24	2,685.6	41.57
SC	3	2.238	24	53.712	0.83
GC	4	2.984	24	71.616	1.11
PST	1	0.746	24	17.904	0.28
AT	125	93.25	24	2,238	34.64
Sludge pump	15	0.746	4	2.984	0.05
Return sludge	22.5	11.19	4	44.76	0.69
Digester (screw pump)	60	44.76	8	358.08	5.54
Filtrate pump	10	3.73	8	29.84	0.46
Effluent lifting station	90	44.76	21	939.96	14.55
SST	1	0.746	24	17.904	0.28
Total	328.5	317.05	–	6,460.36	100.00

Table 7
Estimation of emission factors of the electricity supplied to BMWTP-I

Mode		Capacity (MW)	% Share	EF (kg/$CO_{2\text{-eq}}$/MW)	Emission (kg/$CO_{2\text{-eq}}$)	EF (kg/$CO_{2\text{-eq}}$/MW)
Thermal	Coal	156,190.9	60.37	877.00	136,979,411.0	573.88
	Gas	22,971.25	8.88	353	8,108,851.3	
	Diesel	1,199.75	0.46	604	724,649	
Nuclear		5,780	2.23	17.3	99,994	
Hydro power		40,867.43	15.80	62.4	2,550,127.6	
RES[a]		31,692.14	12.25	0	0	
Total		258,701.5	100.00		148,463,032	

Source: Central Electricity Authority Report January 2015 [24].
[a]Renewable energy resources.

Thus, in Indian scenario, mix mode of power generation exists. Power generation from thermal route (i.e. coal-, gas- or diesel-fuelled power stations) accounts for 60.37% of the total power generation. The remaining power comes from nuclear (2.23%), hydropower (15.8%) and renewable energy resource (12.25%). Employing above power generation scenario, national Emission Factor (EF) for GHG emission is calculated as 573.88 kg $CO_{2\text{-eq}}$/MWh. Accordingly, total GHG emission from the BMWTP-I due to power consumption comes to 3,708 kg $CO_{2\text{-eq}}$ per day.

3.3. Total GHG emissions from BMWTP-I

Total GHG emissions from BMWTP-I could be expressed as summation of on-site and off-site GHG emissions and the same has been shown in Fig. 3. This depicts that on-site GHG emissions for one day operation of BMWTP-I are 14,330 and 3,408 kg $CO_{2\text{-eq}}$ under gas not-flared and flared conditions, respectively. The off-site emissions include emissions due to power supply to the plant to operate various electromechanical equipments at treatment site only. The estimated off-site emissions for BMWTP-I is 3,708 kg $CO_{2\text{-eq}}$ per day. Therefore, in the present case the total GHG emissions would be 18,03 and 7,115 kg $CO_{2\text{-eq}}$ per day under gas not-flared and flared conditions, respectively.

The relative contributions in GHG emissions due to on-site as well as off- site activities are presented in Fig. 3. BMWTP-I emits 18,038 and 7,115 kg $CO_{2\text{-eq}}$/d under not-flared and flared conditions, respectively. The on-site activities that include aerobic activities in AT and anaerobic activities in sludge digester altogether contribute 79.45 and 47.89% under not-flared and flared conditions, respectively. It is evident from Fig. 3, that the total GHG emission as well as percentage share of on-site emissions is very high in case of gas not-flared condition in comparison to gas-flared condition. It is due to the fact that one of the on-site activity i.e. sludge digester emits both the gases CH_4 and CO_2. The GWP of CH_4 is 25 times higher than that of CO_2 [24].

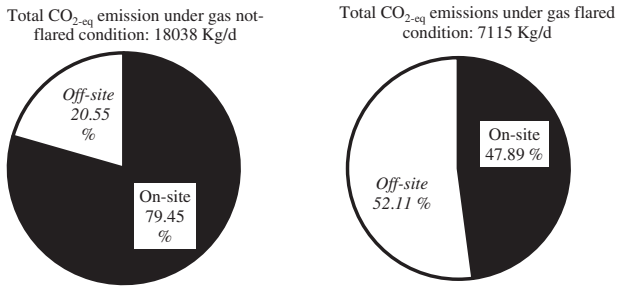

Fig. 3. Comparison of on- and off-site GHG emissions under gas not-flared and flared conditions.

Table 8
Total on-site and off-site GHG emission under gas not-flared and flared conditions

	GHG emissions (kg $CO_{2\text{-eq}}$)	
Total GHG emission expressed as	Gas not-flared	Gas flared
Per Cubic metre wastewater treated	0.90	0.36
Per kg of BOD_5 removed	7.52	2.96
Per Capita per day	0.20	0.08

The GHG emission so computed as above has been expressed in terms of per unit volume of wastewater treated, per unit mass of BOD_5 removed and per capita per day and presented in Table 8. The obtained values are 0.90 kg $CO_{2\text{-eq}}$/m^3, 7.52 kg $CO_{2\text{-eq}}$/kg BOD_5 and 0.20 kg $CO_{2\text{-eq}}$/C-d and 0.36 kg $CO_{2\text{-eq}}$/m^3,

2.96 kg $CO_{2\text{-eq}}$/kg BOD_5 and 0.08 kg $CO_{2\text{-eq}}$/C-d, respectively (Table 8).

Among the above three indicators namely GHG emission per m^3 wastewater treated, per kg BOD_5 removed and per capita per day, the last indicator could be considered great tool to predict the GHG emission quickly from a city having similar wastewater treatment system. This is possible because survey is conducted every decade and population projection can be done using standard methods. In such a way, the above indicator could be utilised for estimation of scenario-based GHG emission over a period.

4. Conclusions

Municipal wastewater treatment plants are recognised as one of the larger minor sources of GHG emissions. In order to control GHG emission from the municipal wastewater treatment plant, it is imperative to identify the on-site as well as off-site activities, which are major contributors of GHG emissions. In view of the above, a case of Beur Municipal Wastewater Treatment Plant Unit I (BMWTP-I) has been considered to estimate carbon-based GHG emissions from various on- and off-site activities. The study indicates that one day operation of BMWTP-I is responsible for 18,038 and 7,115 kg $CO_{2\text{-eq}}$ emissions under not-flared and flared conditions, respectively, out of which 3,708 kg $CO_{2\text{-eq}}$ per day is only due to off-site activities. Off-site GHG emissions due to degradation of biodegradable remains in treated effluent and, transportation and further degradation of digested sludge are neglected. It is evident from the above that under the gas not-flared condition, the on-site and off-site activities contribute 79.45 and 20.55% of the total GHG emission. Whereas, under gas-flared condition, the corresponding figures are 47.89 and 52.11%, respectively.

Two process units namely AT and sludge digester are identified to contribute on-site GHG emissions. Under gas not-flared condition, the contribution of sludge digester is 12,937 kg $CO_{2\text{-eq}}$/d, which is 90.28% of the total on-site GHG emission of 14,330 kg $CO_{2\text{-eq}}$/d. However, under gas-flared condition the contribution of sludge digester has reduced to 2,015 kg $CO_{2\text{-eq}}$/d, which is 59.12% of the total GHG emission of 3,408 kg $CO_{2\text{-eq}}$/d. It clearly shows that by adopting gas flaring system, the contribution of sludge digester is reduced considerably. The GHG emission contribution of sludge digester will be further reduced by utilising the biogas for power generation or for cooking purpose. However, for off-site GHG emissions, 3 out of 11 activities namely, main pumping station, AT and effluent lifting station where major electro-mechanical equipments are installed, contribute major portion i.e. 90.76% of total off-site GHG emission of 3,708 kg $CO_{2\text{-eq}}$/d. The off-site GHG emission could be considerably reduced by installing energy efficient electro-mechanical equipments and optimising the plant operation.

The total GHG emissions from BMWTP-I in terms of per unit volume of wastewater treated, per kg BOD_5 removed and per capita per day are 0.90 kg $CO_{2\text{-eq}}/m^3$, 7.52 kg $CO_{2\text{-eq}}$/kg BOD_5 and 0.20 kg $CO_{2\text{-eq}}$/C-d, respectively, under gas not-flared condition. The corresponding figures under gas-flared conditions are 0.36 kg $CO_{2\text{-eq}}/m^3$, 2.96 kg $CO_{2\text{-eq}}$/kg BOD_5 & 0.08 kg $CO_{2\text{-eq}}$/C-d, respectively. Among the above three indicators, the GHG emission expressed in terms of kg $CO_{2\text{-eq}}$ per capita per day could be considered as a great tool to predict quickly GHG emission from a city adopting the similar treatment process.

References

[1] M. El-Fadel, M. Massoud, Methane emissions from wastewater management, Environ. Pollut. 2 (2001) 114–177.
[2] L. Yerushalmi, M.B. Shahabadi, F. Haghighat, Effect of process parameters on greenhouse gas generation by wastewater treatment plants, Water Environ. Res. 83 (2011) 440–449.
[3] Ecofys, 2013. Available from: <http://www.ecofys.com/files/files/asn-ecofys-2013-world-ghg-emissions-flow-chart-2010.pdf>.
[4] India: Greenhouse Gas Emissions 2007, Ministry of Environment and Forests, Government of India, 2010.
[5] S. Kumar, S.A. Gaikwad, A.V. Shekdar, P.S. Kshirsagar, R.N. Singh, Estimation method for national methane emission from solid waste landfills, Atmos. Environ. 38 (2004) 3481–3487.
[6] A. Sil, S. Kumar, J.W.C. Wong, Development of correction factors for landfill gas emission model suiting Indian condition to predict methane emission from landfills, Bioresour. Technol. 168 (2014) 97–99.
[7] D. Gupta, S.K. Singh, Greenhouse gas emissions from wastewater treatment plants: A case study of Noida, J. Water Sustainability 2 (2012) 131–139.
[8] Intergovernmental Panel on Climate Change, Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, Cambridge University Press, Cambridge, 1997.
[9] U.S. Environmental Protection Agency, Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment, Office of Policy, Planning and Evaluation, U.S. Environmental Protection Agency, Washington, DC, 1997.
[10] L.J.P. Snip, Quantifying the greenhouse gas emissions of waste water treatment plants, MES (Environmental Science), Wageningen University, The Netherlands, Thesis Project Systems and Control, 2010.

[11] H.D. Monteith, H.R. Sahely, H.L. MacLean, D.M. Bagley, A rational procedure for estimation of greenhouse-gas emissions from municipal wastewater treatment plants, Water Environ. Res. 77 (2005) 390–403.
[12] M.B. Shahabadi, L. Yerushalmi, F. Haghighat, Impact of process design on greenhouse gas (GHG) generation by wastewater treatment plants, Water Res. 43 (2009) 2679–2687.
[13] M.B. Shahabadi, L. Yerushalmi, F. Haghighat, Estimation of greenhouse gas generation in wastewater treatment plants—Model development and application, Chemosphere 78 (2010) 1085–1092.
[14] O. Ashrafi, L. Yerushalmi, F. Haghighat, Mathematical modelling of GHG emission in wastewater treatment plants: Steady-state Vs. dynamic, EIC Climate change Technology Conference, (2013).
[15] IPCC 2006, IPCC Guidelines for National Greenhouse Gas Inventories, in: H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, K. Tanabe (Eds.), Prepared by the National Greenhouse Gas Inventories Programme, IGES, Japan, 2006.
[16] G. Mannina, A. Cosenza, R. Gori, R. Sobhani, M. Garrido, D. Rosso, Sensitivity and uncertainty analysis of a plant-wide model for carbon and energy footprint of wastewater treatment plants, 7th International Congress on Environmental Modelling and Software, San Diego, CA, 2014.
[17] R. Gori, L.M. Jiang, R. Sobhani, D. Rosso, Effects of soluble and particulate substrate on the carbon and energy footprint of wastewater treatment processes, Water Res. 45 (2011) 5858–5872.
[18] L. Yerushalmi, M.B. Shahabadi, F. Haghighat, Effect of process parameters on greenhouse gas generation by wastewater treatment plants, Water Environ. Res. 83 (2011) 440–449.
[19] C. Sweetapple, G. Fu, D. Butler, Identifying key sources of uncertainty in the modelling of greenhouse gas emissions from wastewater treatment, Water Res. 47 (2013) 4652–4665.
[20] H.S. Peavy, D.R. Rowe, G. Tchobanoglous, Environmental Engineering, McGraw-Hill International Publications, Civil Engineering Series, Singapore, 1985.
[21] Eddy Metcalf, Wastewater Engineering: Treatment and Reuse, Tata McGraw-Hill edition, New Delhi, 2003.
[22] Manual on Sewerage and Sewage Treatment Systems, Ministry of Urban Development, New Delhi, 2013.
[23] B.E. Rittmann, P.L. McCarty, Environmental Biotechnology: Principles and Applications, McGraw-Hill, Toronto, 2001.
[24] IPCC (2007), Climate change 2007: the physical science basis, in: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (Eds.), Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.
[25] J. Keller, K. Hartley, Greenhouse gas production in wastewater treatment: process selection is the major factor, Water Sci. Technol. 12 (2003) 43–47.
[26] IS 1172-1993: Code of basic requirements for water supply, drainage and sanitation (Fourth Revision), Bureau of Indian Standards (BIS), Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi, 110002.
[27] H.R. Sahely, H.L. MacLean, H.D. Monteith, D.M. Bagley, Comparison of on-site and upstream greenhouse gas emissions from Canadian municipal wastewater treatment facilities, J. Environ. Eng. Sci. 5 (2006) 405–415.
[28] Y. Wei, L. Yerushalmi, F. Haghighat, Estimation of greenhouse gas emissions by the wastewater treatment plant of a locomotive repair factory in China, Water Environ. Res. 80 (2008) 2253–2260.
[29] Central Electrical Authority, 2015. Available from: <http://www.cea.nic.in/report.html>.