Greenhouse gas emission details and cost analysis of existing and alternative waste management systems (WMSs) in Kabul city

Section 1. Collection and transportation

(1) Greenhouse gas emissions

Greenhouse gas emissions from waste collection and transport (ton-CO_2/year) are calculated as

$$\text{Total GHG emissions} = TFC \times Q \times GWP \quad (1)$$

where TFC represents the total fuel consumption (L/day) used for collection of mixed waste and recyclables, Q is the emission factor from diesel, and GWP is the equivalence factor based on carbon dioxide as 1. To calculate TFC, we used

$$TFC = TFC_{M\_W} + TFC_R, \quad (2)$$

where TFC_{M_W} represents the amount of fuel consumption (L/day) used for collection of mixed waste; TFC_R (L/day) represents the collection of recyclables. To calculate TFC_{M_W} and TFC_R, the following equation was used.

$$TFC_{M\_W} = X_{M\_W} \times FC_{M\_W} \quad (3)$$

Therein, X_{M_W} denotes the amount of mixed waste (ton/day) collected, and FC_{M_W} stands for the unit value of fuel consumption with a loading factor of 100% (L/ton).

$$TFC_R = N_i \times D \times FC \quad (4)$$

In the equation above, N stands for the number of trucks, $_i$ represents the pattern of collection, D denotes the average travel distance of round trip (km), and FC expresses the unit value of fuel consumption with a loading factor of 100% (L/km).

Note: To obtain the number of trucks for collection of recyclables in S-0, equation (5) was used. For S-3 and S-4, equation (6) was applied.

$$N_{RS\text{-}MRF} = \text{Roundup}\,(X_R / C / f) \quad (5)$$

$$N_{D.C\text{-}MRF} = (X_R / Y / f) \quad (6)$$

Therein, X_R signifies the amount of recyclables (ton/day), C denotes the capacity of truck (ton), f stands for the frequency (1/day), $_{RS\text{-}MRF}$ expresses the number of trucks used for collection from recycling shops to MRF, Y represents the amount of recyclables (ton/day) generated in different districts, and $_{D.C\text{-}MRF}$ denotes the collection of reyclabes from district centers to MRF. Following are the descriptions of the respective scenarios with their fuel consumption.

S-0: In the baseline scenario, the amount of mixed waste collected from collection points and transported to the landfill site is 1,314 ton/day, with an average fuel consumption of 8,048 L/day, meaning that the fuel consumption per ton of mixed waste in collection is 6.12 L/ton. Consequently, to calculate the amount of fuel consumption on mixed waste collection, equation (3) was considered.

Because waste collection of recyclables differs from mixed materials, from recycling shops to recycling facilities and then their residues to landfill site, equations (4) and (5) have been considered for calculation of the fuel consumption. Detailed calculations of equations (4) and (5) are presented with results in Tables S1 and S2 including the designed models, assumptions, and the values of variables.

Table A1. Diesel consumption for collection of recyclables in S-0

Amount of waste (ton /day), X_R	22.7
Capacity of truck (ton), C	12
Frequency (1/day), f	1
Number of trucks (number), $N_{RS\text{-}MRF}$	2
* Average travel distance of round trip (km), D	72
* Fuel consumption of truck (L/km), FC	0.5
Total fuel consumption (L/day), $TFC_{RS\text{-}MRF}$	72

Table S2. Diesel consumption for collection of residues in S-0

Amount of waste (ton/day), X_R	5
Capacity of truck (ton), C	5
Frequency (1/day), f	1
Number of trucks (number), $N_{R\text{-}S0}$	1
Average travel distance of round trip (km), D	38
* Fuel consumption of truck (L/km), FC	0.3
Total fuel consumption (L/day), $TFC_{MRF\text{-}L}$	11.4

*Department of sanitation (DoS) of Kabul city (2020)

* DOS of Kabul city (2020)

S-1 and S-2: Total fuel consumption was estimated based on equation (3). X_{M_W} was found by calculation by multiplying the total population of Kabul, 4.67 million. The waste generation per capita per day was 0.54 kg.

S-3 and S-4: In this scenario, to calculate the amount of fuel consumption on mixed waste collection, equation (3) was considered, while regarding recyclables, for which the collection starts from the center of city districts to MRF / landfill site, equation (4) and (6) have been incorporated. Detailed calculations of equations (4) and (6) are presented with the results in Table A3 including the designed models, assumptions, and the variable values. In addition, the average travel distance D (km) has been modelled and calculated using GIS Network Analysis technique. Figure 2 depicts routing maps of waste collection on a source-separated system. Table A4 presents routing map details.

Table S3. Calculated fuel diesel consumption for collection and transport of source-separated waste recyclables from the center of city districts to recycling facilities in S-3

Amount of waste (ton/day), X_R	227
Loaded waste onto truck (ton/day) based on routes (ton), Y	-
Frequency (1/day), f	1
Number of trucks (number), $N_{R\text{-}S3,\ S4}$	20

Average travel distance of round trip (km), D	79
Fuel consumption of truck (L/km), FC	0.5
Total fuel consumption (L/day), $TFC_{D.C\text{-}MRF}$	774.2

Note: One truck has a 4-ton capacity. Its fuel consumption per km is 0.3 L/km according to DoS. Other trucks have a 12-ton capacity.

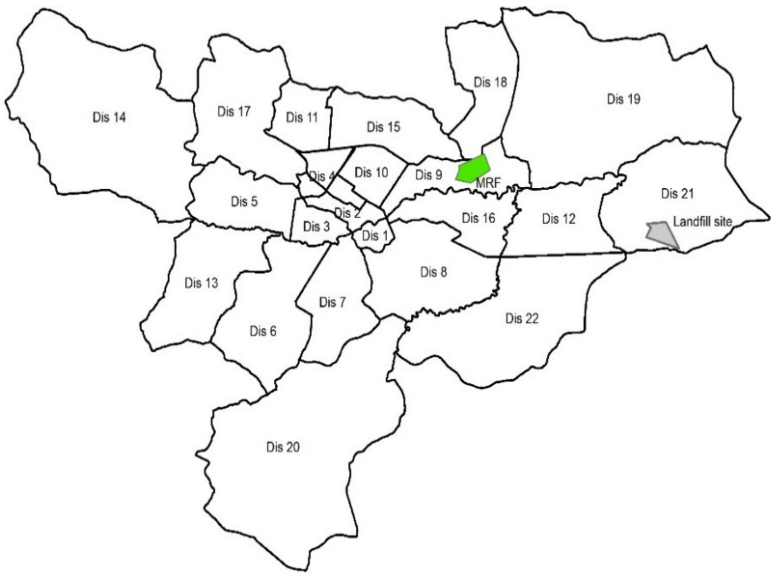

Figure S1. Locations of current recycling facilities and landfill sites in Kabul city.

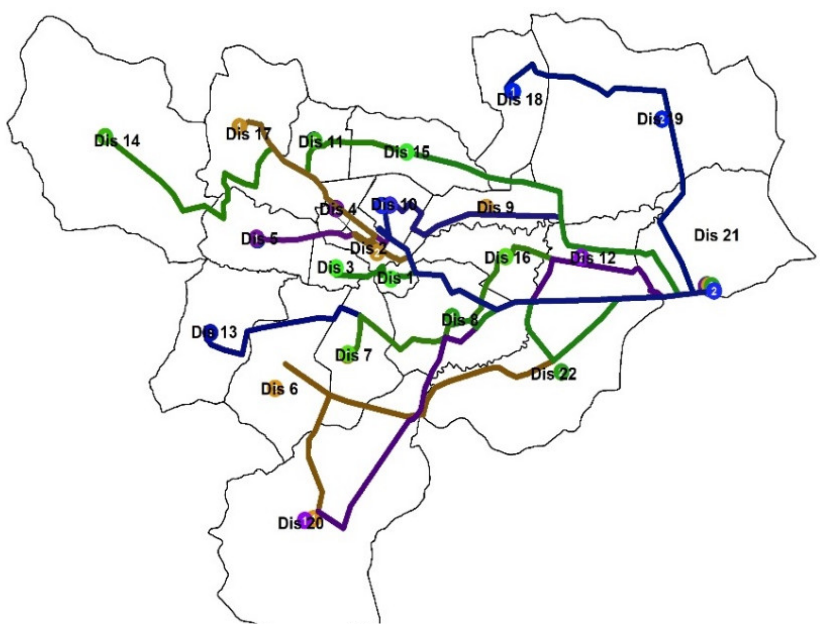

Figure S2. Routing map of collection and transport on source-separated waste from collection points/ center of a district to landfill site.

Table S4. Network analysis showing route distances generated from collection points / center of city districts of source-separated waste to landfill site

S.no.	Start point	Intermediat-e point	End point	Route	Round trip (km)	** Fuel consumption (L/km)	Fuel consumpti-on (L)	Waste amount collected (ton/day)
1	^Dis 3	Dis 1	Dumpsite	R1	99	0.5	49	11
2	Dis 4	-	Dumpsite	R2	70	0.5	35	12
3	Dis 4	-	Dumpsite	R2	70	0.5	35	12
4	Dis 5	-	Dumpsite	R3	80	0.5	40	12
5	Dis 5	Dis 4	Dumpsite	R4	93	0.5	47	12
6	Dis 7	-	Dumpsite	R5	70	0.5	35	12
7	Dis 9	-	Dumpsite	R6	51	0.5	25	12
8	Dis 10	Dis 9	Dumpsite	R7	69	0.5	34	10
9	Dis 11	-	Dumpsite	R8	77	0.5	38	12
10	Dis 13	-	Dumpsite	R9	90	0.5	45	12
11	Dis 14	Dis 11	Dumpsite	R10	122	0.5	61	12
12	Dis 15	-	Dumpsite	R11	65	0.5	32	11
13	Dis 15	-	Dumpsite	R11	65	0.5	32	11
14	Dis 7	Dis 16	Dumpsite	R12	79	0.5	39	12
15	Dis 17	Dis 2	Dumpsite	R13	101	0.5	51	12
16	Dis 18	Dis 19	Dumpsite	R14	69	0.3	34	4
17	Dis 20	Dis 6	Dumpsite	R15	101	0.5	51	12
18	Dis 20	Dis 12	Dumpsite	R16	89	0.5	45	12
19	Dis 8	Dis 22	Dumpsite	R17	59	0.5	30	12
20	Dis 10	-	Dumpsite	R 18	70	0.5	35	12
	Total				1,588		793.8	227
	Average (km)				79			

^Dis stands for district.

The following tables show total fuel consumption of waste collection for each scenario and the amounts of GHG emissions during this process on each scenario.

Table S5. Estimation of total fuel consumption for waste collection in existing and alternative scenarios

Scenarios	Fuel consumption for recyclables collection (L/day)	Fuel consumption for mixed waste collection(L/day)	Total (L/day)
Baseline scenarios	83.4	8,048	8,131.4
Scenario 1	-	15,477	15,477
Scenario 2	-	15,477	15,477
Scenario 3	774.2	14,073.37	14,847.57
Scenario 4	774.2	14,073.37	14,847.57

Table A6. Estimation the GHG emissions of waste collection for existing and alternative scenarios

Scenarios	Impact category (CO_2)	Unit	Total
Baseline scenario	Global Warming	ton CO_2 /year	7,899.89
Scenario 1			15,036.35
Scenario 2			15,036.35
Scenario 3			14,424.84
Scenario 4			14,424.84

Note: Gaseous emissions from diesel fuel (2663 g/L) of CO_2 were obtained from Kebin et al. (2010) and Babu et al. (2014). Characterization factors are based on IPCC model 2007 for a 100-year time horizon.

(2) Cost analysis of collection

To calculate costs increased by the increased level of waste collection services to 100%, we use

$$TCoAWC = A + B + C + D + E, \tag{7}$$

where TCoAWC shows the total costs of alternative waste collection (S/year), A denotes the cost of collection trucks (\$/year), B stands for the cost of collection trucks maintenance (\$/year), C signifies the cost of diesel fuel for collection trucks (\$/year), D represents the salary cost (\$/year), and E expresses the cost for working tools, clothing, and training (\$/year). The respective calculations of these variables are presented hereinafter.

A. Cost of collection truck

The cost of collection trucks has been calculated using the following equation.

$$A = A1 + A2 \tag{8}$$

Therein, A1 represents the cost of collection trucks (\$/year) that collect mixed waste, wherease A2 (\$/year) is that for recyclables. To calculate A1 and A2, the equations are used.

$$A1 = \text{Roundup}\,(X_{M\_w} / (C \times f)) \times (B/L) \tag{9}$$

Therein, X_{M_W} represents the amount of uncollected mixed waste (ton/day), C denotes the truck capacity (ton), f is the frequency (trip) of truck (1/day), B stands for the cost per unit of truck (\$/truck), and L signifies the life time of vehicle trucks (year). Also,

$$A2 = N_{R\text{-}S3,\,S4} \times B/L\,, \tag{10}$$

where $N_{R\text{-}S3,\,S4}$ represents the number of trucks (number) as calculated using equation (6).

S-1 and S-2: In these scenarios, because all the waste has been assumed to be collected in mixed waste, there is only cost related to A1. Table A7 shows descriptions of the designed model, assumptions, and the variable values including the result in this regard.

Table S7. Cost calculations of added trucks for mixed waste collection in S-1 and S-2

Items	Amount
Amount of waste (ton/day), X_{M_W}	1200.33
Capacity of truck (ton/truck), C	12
Frequency (1/day), f	1
* Cost per unit of truck ($/truck), B	25,000
Lifetime of truck (year), L	15
Total ($/year)	168,333

* DoS of Kabul city (2020)

S-3 and S-4: In these scenarios, cost calculations of added trucks have been considered based on the total cost calculations of A1 and A2. Tables A8 and A9 show descriptions of the designed model, assumptions and the variable values including the results.

Table S8. Cost calculation of added trucks for mixed waste collection in S-3

Items	Amount
Amount of waste (ton/day), X_{M_W}	973
Capacity of truck (ton), C	12
Frequency (1/day), f	1
Cost per unit of truck ($), B	25,000
Lifetime of truck (year), L	15
Total ($/year)	136,666.7

Table S9. Cost calculation of added trucks for recyclables collection in S-3

Items	Amount
Number of trucks (ton), $N_{R\text{-}S3\ ,\ S4}$	20
Frequency (1/day), f	1
Cost per unit of truck ($), B	25,000
Lifetime of truck (year), L	15
Total ($/year)	33,333

B. Cost of collection trucks maintenance

Following is the formula for calculating the cost of collection truck maintenance ($/year) in the scenarios.

$$B = N \times MC \qquad (11)$$

In that equation, N is number of trucks (number) and MC ($/year) is the maintenance cost of trucks. Calculation of the number of trucks for the collection of mixed waste is based on Roundup (X_{M_W}/ (C × f)). Their explanations including the values are presented in Tables A7 and A8. For recyclables the value of N is shown in Table A9.

C. Cost of fuel for collection trucks

Following is the formula for the cost of fuel for collection trucks (C) ($/year) of the scenarios.

$$C = TFC \times DP \quad (12)$$

As shown there, TFC is the total fuel consumption (L/year), which is shown in Table A5 (L/day). Also, DP represents the diesel price, which is 0.49 $/L, as obtained from a survey interview (2020).

D. Salary cost

Following is the formula to calculate the salary cost.

$$D = D1 + D2 \quad (13)$$

Therein, D1 stands for the salary cost for mixed waste collection ($/year), and D2 denotes that for recyclables ($/year). To calculate D1 and D2, the following equations are used.

$$D1 = X \times NW \times S \quad (14)$$

In that equation, X represents the amount of mixed waste (ton/day), and NW denotes the number of workers per ton of mixed waste (workers/ton/day). Also, S is the salary per worker ($/worker/year).

$$D2 = (NW_{S\text{-}H} + NW_{Dis\_MRF} + OW) \times S \quad (15)$$

As shown there, $NW_{S\text{-}H}$ denotes the number of workers for collection of recyclables at the level of households, NW_{Dis_MRF} is the number of workers for collection of recyclables from districts to MRF, and OW is the number of office workers.

The total number of workers to be formalized in $NW_{S\text{-}H}$ has been formulated as

$$NW_{S\text{-}H} = TNH / (WD \times NFW \times F), \quad (16)$$

where TNH denotes the total number that households in Kabul city are visited for their waste recyclables (number/year), WD represents the number of working days (days/year), NFW is the number of households covered per formalized worker (number of households /worker/day), and F stands for the frequency of collection (1/week). To obtain NFW, we started to find the number of households to have their recyclables collected per formalized worker. To do so, the following formula is used.

$$NFW = (WH - 1) / T \quad (17)$$

Therein, WH represents the working hours (h/day), and T (h) is the time spent to collect the recyclables per household, Which includes receiving waste from the household and walking to the next household. Also, (-1) represents the one hour break.

For the calcuation of NW_{Dis}

$$NW_{Dis\_MRF} = \sum NT \times NW_{R\_T}, \quad (18)$$

where NT stands for the number of trucks, and NW_{R_T} denotes the number of workers allocated to each truck. To ascertain the number of office workers (OW) integrated in this process, on average, four office workers might be necessary to manage the clerical and administrative tasks of 150 waste collection workers.

$$OW= (NW_{S\text{-}H} + NW_{Dis}\_MRF)/OWsub \qquad (19)$$

In the baseline scenario, there are 2,415 workers - with a salary of $ 141 per month, able to collect 1,314 ton of waste per day as mixed materials. In fact, for the collection of 1 ton of waste, 1.84 workers have been assigned. This number of workers has been examined from calculation of the salary cost related to mixed waste collection for alternative scenarios. However, this number (1.84 workers /ton) cannot be used to calculate the salary cost in source-separated system because there is house-to-house collection, with wastes then taken to the center of each district before being sent to MRF: something which differs from the process used for mixed waste collection.

Below are the cost calculations of labor for the respective scenarios.

S-1 and S-2: The following table shows descriptions of the designed model, assumptions, variable values, and results.

Table S10. Salary costs for integrating informal workers in mixed waste collection in S-1 and S-2

Amount of waste (ton/day), X	1200.33
* Number of workers per ton of mixed waste collected (worker/ ton/day), NW	1.84
Salary ($/worker/year), S	1,230.77
Total ($/year)	2,715,621

* Salary is inferred as 102.56 $ /month for integrated workers.

S-3 and S-4: Following are the descriptions of the designed model, assumptions, variable values, and results.

Table S11. Salary cost for the integration of informal workers in mixed waste collection in S3 and S4

Amount of waste (ton/day), X	973
Number of workers per ton of mixed waste collected (worker/ ton/day), NW	1.84
Salary ($/worker/year), S	1,230.77
Total ($/year)	2,203,472

Table S12. Total number of households covered by a formalized workers for collection of source-separated waste

Working hours (h), WH	8
Time spent for collection (h/household), T	0.05

Household number (number of households /worker/day), NFW	140

Note: One-hour break was considered for serving and prayers.

Table S13 Total number informal workers to be integrated in collection of sources separated waste from house to house

Parameter	amount	unit
Kabul city oopulation	4,679,648	number
Household number	7	number /family
Number households in Kabul city	668,521	number
TNH = total number of households of Kabul city are visited	244,010,217	number/year
Amount of waste recyclable generation	455	ton /day
Efficiency of source separation	0.5	%
F = frequency of recyclables collection	1	visit/week
Production of recyclables per family	0.680	kg/family / day
NFW = number of households covered per formalized worker in collection of source-separated waste per day	140	No. of households / formalized worker/day
WD = number of working days in a year	261	day/year
NW_{S-H} = number of formalized workers for collection of sources separated waste	954	number

Table S14. Number of informal workers to be integrated in collection and transport of recyclabes from district centers to MRF/ landfill site

Total number of workers for 12 ton type truck		Total number of workers for 4 ton type truck		Grand total (number)
number of trucks, N	19	number of trucks, N	1	
number of workers on a truck, NW_{R_T}	6	number of workers on a truck, NW_{R_T}	1	
subtotal	114	subtotal	4	118

* According to DoS and the World Bank report of 2016, 6 workers on large size trucks and 4 on a small one were assigned to load the waste to trucks. Based on that, we assumed 6 workers for a large truck (12 ton), and 4 for small size truck (4 ton).

Table S15. Total number of informal workers integrated as office workers in source-separated waste collection and transport

Number of staff on collection of sources separated waste from house to house, NW_{S-H}	954
Number of workers for collection and transport from waste collection points to MRF/landfill, NW_{Dis_MRF}	118
Number office workers for 150 waste collection workers, OWsub	4
Office workers, OW (number)	29

E. Costs for working tools, clothing, and training

Following is the formula used to calculate these costs in these scenarios.

$$E = NW \times C_{TCT} \quad (20)$$

In that equation, NW stands for the number of workers to be integrated in the scenario as found from the salary cost, and C_{TCT} denotes the cost for working tools, clothing and training ($/ formalized worker/year). The value of the C_{TCT} variable is $ 68.6, which was obtained from DoS.

F. Total costs of alternative waste collection (TCoAWC)

Following are tables showing the total costs of waste collection for alterative scenarios.

Table S16. Cost calculation of waste collection of S-1 and S-2 in WMS ($/year)

Items	Integrated cost ($/year)	Existing waste collection ($/year)	Total annual cost ($/year)
Salary ($/person/year)	2,715,621	4,086,923.08	6,802,544
Working tools, clothing and training ($/ formalized worker)	151,362	165,669	317,031
Cost of trucks ($/truck)	168,333	-	168,333
Vehicle maintenance ($/year)	305,828	1,132,429	1,438,257
Diesel fuel consumption ($/L)	1,328,677	1,045,033	2,373,710
Total			11,099,875

Source: [1] Cost of a second-hand truck is $25,000, according to DoS officials (2020) with the assumption of a 15-year lifetime.

Table S17. Cost calculation of waste collection of S-3 and S-4 WMS ($/year)

Items	Integrated cost ($/year)	Existing waste collection ($/year)	Total annual cost ($/year)
Salary ($/person/year)	3,592,183	6,134,615.38	7,679,106
Working tools, clothing and training ($/ formalized worker)	200,219	258,203.68	365,888
Cost of trucks ($/truck)	170,000	-	170000
Maintenance of the vehicles ($/year)	308,856	1,132,428.62	1,441,285
Diesel fuel consumption ($/L)	1,219,578	1,045,032.80	2,264,611
Total			11,920,890

Section 2. MRF/recycling

(1) Greenhouse gas emissions

For the calculation of GHG emissions (ton CO_2 eq/year) of MRF at different scenarios, following are the related equations.

$$\text{Total GHG emissions} = \sum T_{Electricity} \times Q_i \times GWPi + \sum TFC \times Mi \times GWPi \quad (21)$$

Therein, $T_{Electricity}$ signifies the total amount of electric energy using on the recycling treatment(kWh/day), Q_i stands for the mass of GHG emissions from electricity (kg CO_2/day) where i is assigned for a category, GWP expresses the equivalence factor based on carbon dioxide as 1, TFC represents the total amount of diesel consuming on recycling treatment (L/day), and Mi denotes gaseous emissions from diesel fuel (kg CO_2/day). The total amount of electricity and diesel fuel are calculated as

$$T_{Electricity} = X \times A \quad \text{and} \quad (22)$$

$$TFC = X \times B, \quad (23)$$

where X represents the amount of waste (ton/day) taken at MRF, A represents the electricity consumption per ton of waste (kWh/ton), and B denotes the diesel use per ton of waste (L/ton). Furthermore, to calculate the avoided GHG emissions from equivalent amount of materials production from virgin processes, the following equation was applied. It incorporates the IDEA database of MILCA software.

$$\text{Total GHG emissions} = \sum TA_R \times PC_i \times GHG \quad (24)$$

In that equation, TA_R is the amount of recyclable materials recovered from recycling process(ton/day), PC_i represents the parentage compositions of waste recyclables within the total amount (100%) of recyclables (see Table A18), and i is the type of material. Residues were considered as inert materials. Characterization factors are based on IPCC moldel 2007 for a 100-year time horizon.

Equation 22 has shown Net GHG emissions from recycling treatment as shown below.

$$\text{Net GHG emissions (kg CO2eq)} = \text{Equation (21)} - \text{Equation (24)} \quad (25)$$

Table S18. Percentage compositions of waste recyclables among the total amount (%) of recyclables

component	composition (%)
glass	11
plastic	39
metal	22
paper	28

The following tables show descriptions of the designed model, assumptions, variable values, and calculations related to recycling treatments in different scenarios.

Table S19. Model designed for calculating parameters of recycling of waste in S0

Parameters	Amount	Unit	Source
Total percentage of recyclable materials in household waste	18	%	Azimi and Matsumoto, 2017
Sorting efficiency at MRF	95	%	-
Recycling rate	80	%	-
* Consumption of diesel for operations, B	3.21	L/ton	Rajaeifar et al., 2015
* Consumption of electricity for operations, A	3.2	kWh/ton	Rajaeifar et al., 2015
Waste amount of dry recyclables to be sorted at MRF, X	=0.009 × 2527	t	calculation
Waste amount of dry recyclables to be sorted at MRF, X	22.74	t	calculation
Waste amount of dry recyclables recovered by sorting process	=22.743 × 0.95 × 10^-3	Gg	calculation
Waste amount of dry recyclables recovered by sorting process	0.02160585	Gg	calculation
Amount of dry recyclable materials recovered from recycling process (avoided material), TA_R	=0.02160585 × 0.8	Gg	calculation
** Amount of dry recyclable materials recovered from recycling process (avoided material), TA_R	0.01728468	Gg	calculation
Avoided glass materials	1,920.52	kg	calculation
Avoided plastic materials	6,721.82	kg	calculation
Avoided metal materials	3,841.04	kg	calculation
Avoided paper materials	4,801.3	kg	calculation
Consumption of diesel for operations, TFC	73	L	calculation
*** Consumption of diesel for operations,	2,694	MJ	calculation
Consumption of electricity for operations, $T_{Electricity}$	73	kWh	calculation
Total amount of recycling materials	17,285	kg	calculation
Total amount of recycling materials, TA_R	17	ton	calculation
*** Residues	5.5	ton	calculation

Source: Rajaeifar, M.A.; Tabatabaei, M.; Ghanavati, H.; Khoshnevisan, B.; Rafiee, S. Comparative life cycle assessment of different municipal solid waste management scenarios in Iran. *Renew. Sust. Energ. Rev.* **2015**, *51*, 886–898.

** For the calculation of each avoided material, we multiplied the total amount of recyclable materials recovered from recycling process by their percentage compositions in household waste, as Table A19 has shown the compositions of recyclable materials.
*** For changing the amount of fuel into energy, we multiplied that by 36.9 MJ, which is the energy value of diesel fuel in L.
**** Residues are considered as inert materials when being landfilled. For that reason, only emissions related with fuel consumption were considered during landfilling.
We considered higher efficiency because two separations were conducted before going to MRF. In addition, the reference was given in Table A17

Note: In Table A19, we linked the variables in this table with the variables included in the formula above. Therefore, please follow this when you want to link the variables of other tables with the formula ones.

Table S20. Model designed for calcuating the paramaters for recycling of waste in S2

Parameter	amount	unit	* source
Total percentage of recyclable materials in HSW	18	%	-
Sorting efficiency at MRF	70	%	-
Recycling rate	70	%	-
Consumption of diesel for operations	3.21	L/ton	-
Consumption of electricity for operations	3.2	kWh/ton	-
Waste amount of mixed waste to be sorted at MRF	=2527 × 10^-3	Gg	calculation
Waste amount of mixed waste to be sorted at MRF	2.527	Gg	calculation
Waste amount of dry recyclables recovered by sorting process	=2527 × 0.18 × 0.7 × 10^-3	Gg	calculation
Waste amount of dry recyclables recovered by sorting process	0.318402	Gg	calculation
Amount of dry recyclable materials recovered from recycling process (avoided material)	=0.318402 × 0.7	Gg	calculation
Amount of dry recyclable materials recovered from recycling process (avoided material)	0.2228814	Gg	calculation
Avoided glass materials	2,4764.6	kg	calculation
Avoided plastic materials	8,6676.1	kg	calculation
Avoided metal materials	49,529.2	kg	calculation
Avoided paper materials	61,911.5	kg	calculation
Consumption of diesel for operations per day	8,111.67	L	calculation
Consumption of diesel for operations per day	299,320.62	MJ	calculation
Total consumption of electricity for operations	8,086.4	kWh	calculation
Total amount of recycling materials	222.88	ton	calculation
Total amount of residuals	95.5	ton	calculation

* Some parameters have no written references because they are described above.

Table A21. Model designed for calcuating the paramaters in recycling of wastes in S3 and S4

Parameter	amount	unit	source
Total percentage of recyclable materials in HSW	18	%	-
Efficiency of source-separation of recyclables	50	%	-
* Sorting efficiency at MRF from mixed recyclables	84	%	-
recycling rate	92	%	-
Consumption of diesel for operations	3.21	L/ton	-
Consumption of electricity for operations	3.2	kWh/ton	-
Waste amount of dry recyclables to be sorted at MRF	=2527 × 0.18 × 0.5 × 10^-3	Gg	calculation
Waste amount of dry recyclables to be sorted at MRF	0.22743	Gg	calculation
Waste amount of dry recyclables recovered by sorting process	0.22743 × 0.84	Gg	calculation
Waste amount of dry recyclables recovered by sorting process	0.1910412	Gg	calculation
Amount of dry recyclable materials recovered from recycling processes (avoided material)	0.1910412 × 0.92		calculation
Amount of dry recyclable materials recovered from recycling processes (avoided material)	0.175757904	Gg	calculation
Avoided glass materials	19528.66	kg	calculation
Avoided plastic materials	68350.296	kg	calculation
Avoided metal materials	39057.31	kg	calculation
Avoided paper materials	48821.64	kg	calculation
Total consumption of diesel for operations	730.05	L	calculation
Total consumption of diesel for operations	26938.86	MJ	calculation
Total consumption of electricity for operations	727.78	kWh	calculation
Total amount of recycling materials	175.76	ton	calculation
Total amount of residuals	51.67	ton	calculation

* For how it was selected this percent, please consult Table A22. We considered the average rate of efficiencies between minimum and maximum.

Table S22. Averaging manual sorting efficiency at MRF for source-separated waste

material	minimum recovery efficiency (%)	maximum recovery efficiency (%)	average (%)
paper	60	95	78
glass	70	95	83
plastic	80	95	88
metal	80	95	88
Average rate of efficiency of MRF (%)	-	-	83.75

Source: Design of a Materials Recovery Facility (MRF) For Processing the Recyclable Materials of New York City's Municipal Solid Waste (2000).

Table S23. Estimation the GHG emissions of recycling waste treatment of different scenarios

Scenarios	Impact category (CO_2eq)	Unit	Recycling	Avoided emissions	Net emission
Baseline scenario	Global Warming	ton CO2 eq/year	85.03	13,302.92	-13,217.89
Scenario 1			-	-	0.00
Scenario 2			9,947.82	171,537.64	-161,589.82
Scenario 3			895.30	135,269.68	-134,374.37
Scenario 4			895.30	135,269.68	-134,374.37

(2) Cost

For calculating costs borne because of recycling treatment including the integration of informal workers, the following equation has been applied.

$$TCoWR = A + B + C \quad (26)$$

In that equation, TCoWR represents the total cost of waste recycling ($/year), A denotes the cost of electricity and diesel fuel ($ /year), B stands for the salary cost ($ /year), and C is the total cost for working tools, clothing, and training ($/year)

A. Cost of electricity and diesel fuel for recycling treatment

Following is the formula for the cost of electricity and diesel fuel for waste recycling.

$$A = C_{Electricity} + C_D \quad (27)$$

Therein, $C_{Electricity}$ signifies the total cost of electricity (kWh/year) and C_D ($/ year) expresses the total cost of diesel consumption. These were found using the equations below as

$$C_{Electricity} = X \times EL \times EP \text{ and} \quad (28)$$

$$C_D = X \times D \times DP , \quad (29)$$

where X stands for the amount of waste (ton/day), EL denotes the unit value of electricity use (kWh/ton), EP represents the electricity price ($/kWh), 365 signifies the conversion factor into year, D denotes the unit value of diesel consumption (L)/day), and DP stands for the diesel price ($/L). Values of EP (0.16) and DP (0.49) were obtained through an interview survey.

B. Salary cost

Following is the formula which has been applied for calcuating the salary cost for integration of informal workers into the formalized system at MRF for waste reycling.

$$B = (X/y) \times S \quad (30)$$

Here, B represents the salary cost of integeared workers ($/year), X denotes the amount of waste taken to MRF (ton/day), y stands for the average rate of sorting (tones/person/day), and S expresses the salary cost per formalized worker ($/person/year).

Below are the cost calculations of labor for each scenario:

S-2: Following table shows the descriptions of the designed model, assumptions, variable values and results.

Table S24. Salary cost for the integration of informal workers for recycling process at MRF in S-2

Item	Amount
Amount of waste collected to MRF (ton/day), X	2,527
* Average rate of sorting at MRF (tones/person/day), y	5.12
Salary ($/year), S	1,230.77
Total ($/year), B	607,451.92

Source: "Integrated Solid Waste management – A Life Cycle Inventory". White et al. (1995), Chapman & Hall, London; and Ministry of Urban Development Government of India (2000).

S-3 and S-4: In the case of source-separated waste materials at MRF, first we found the average sorting rate amount per person per day (tons/day/person) (Table A25) as

$$y = SR_i \times (WH-1), \quad (31)$$

where SR denotes the average range of sorting rate of each recyclable material at MRF; i is their category. Also, WH represents the working hours, which are 8 h/day, with (-1) one hour break time for serving and prayers.

Table S25. Average amounts of sorting of source-separated materials at MRF (ton/day/person)

Material	Range of sorting rate (tons/hours/person)		Average sorting
Paper (tons/hours/person)	0.75	5.00	2.88
Glass, tons/hours/person)	0.45	0.90	0.68
Plastics, tons/hours/person)	0.15	0.30	0.23
Aluminum (tons/hours/person)	0.05	0.06	0.06
Overall average of sorting at MRF per person per day (tons/day/person)			y = 6.70

Table S26. Total number of workers to be integrated for processes on source-separated waste at MRF

Item	Amount
Waste amount (ton/ year), X	82964.5
average rate of sorting (ton/day/person), y	6.7
Salary ($/year), S	1,230.77
Total, B ($/year)	58,370.26

Note: We regarded 261 days/year as working days after excluding weekends.

C. Costs for working tools, clothing and training

Following is the formula to calculate this cost in the scenarios.

$$C = NW \times C_{TCT} \quad (32)$$

In that equation, NW stands for the total number of workers to be integrated at MRF, and C_{TCT} denotes the cost for working tools, clothing and training ($/ formalized worker/year). NW is calculable by X/y , which is defined at section B (salary cost). The value of C_{TCT} variable is 68.6 $/year, as obtained from DoS.

D. Total cost of waste recycling (TCoWR)

The following tables are cost calculations for waste recycling / MRF and revenues from the sale of recyclables of the scenarios.

Table S27. Cost calculation of waste recycling treatment in S-2 of WMS ($/year)

Parameter	Total annual cost ($/year)
Salary ($/person/year)	607,451.92
Working tools, clothing and training ($/ formalized worker)	33,857.85
Electricity cost for recycling process ($/year)	473,002.56
Diesel cost for recycling process ($/year)	1,450,772.18
Total	2,565,084.52

Table S28. Cost calculation of waste recycling treatment in S-3 and S-4 of WMS ($/year)

Parameter	Total annual cost ($/year)
Salary ($/person/year)	58,370.26
Working tools, clothing and training ($/ formalized worker)	3,253.41
Electricity cost for recycling process ($/year)	42,570.23
Diesel cost for recycling process ($/year)	130,569.50
Total	234,763.40

E. Cost revenues from sales of recycled materials

Following is the formula for calculating revenues from sales of recycled products.

$$CR = \Sigma (Mi \times Pj) \quad (33)$$

In that equation, CR represents the total cost of revenues ($/year); Mi dentos the recycled materials at MRF (ton/day), i is assigned for the type of material, P stands for the market price of materials per ton ($/ton), with j representing the category.

Table S29. Annual revenue from the sale of recyclables in S-2

Material	Amount recycled (ton/day), M	* Market price ($/ton)	Total revenue ($/year)
Glass	24.76	256.41	2,317,712.56
Plastic	86.68	128.21	4,055,996.99
Metal	49.53	256.41	4,635,425.13
Paper	61.91	51.28	1,158,856.28
Total			12,167,990.96

* Source survey interview (2020)

Table S30. Annual revenue from the sale of recyclables in S-3 and S-4

Material	Amount recycled (ton/day)	Market price ($/ton)	Total revenue ($/year)
Glass	19.53	256.41	1,827,681.91
Plastic	68.35	128.21	3,198,443.34
Metal	39.06	256.41	3,655,363.82
Paper	48.82	51.28	913,840.95
Total			9,595,330.02

Section 3. Landfilling

(1) Greenhouse gas emissions

Because landfill gas emissions mainly consist of CO_2 and CH_4 ,but because CO_2 has biogenic origin and we did not consider that in the system boundary of the study. Therefore, we only calculated the emissions associated with CH_4 gas. Calculation of CH_4 emissions was conducted based on the IPCC default method as

$$CH_4 = (HWDS \times DOC \times MCF \times DOC_F \times F \times 16/12 - R)\ (1- OX), \tag{34}$$

where HWDS represents fraction of HW interred at disposal sites, MCF stands for the methane correction factor, DOC denotes is the degradable organic carbon fraction, DOC_F expresses the fraction of degradable organic carbon that ultimately is degraded and released, F is the fraction of CH_4 in Landfill gas by volume, R expresses the recovered CH_4, and 16/12 is the molecular weight ratio of CH_4/C. Also, OX is the oxidation factor. The default values for calculating the CH_4 release from open dumps are followed by 0.4, 0.77, 0 and 50%, respectively, for MCF, DOC_F, OX and F. For CH_4 estimation for unsanitary landfilling, the default value of MCF was selected 0.6 because the current landfill activities are similar to the uncategorized management approach, which is neither to managed or unmanaged disposal sites, based on IPCC report standards. However, in sanitary landfill, this value is 1 because it is a managed site. The amount of diesel use at landfilling has been calculated using the following equation.

$$TFC = X \times A \tag{35}$$

Here, TFC is the total fuel use on landfilling the waste (L/day), X represents the amount of waste (ton/day), and A denotes the unit value of fuel consumption at landfilling (L/ton).

The amount of diesel consumed at an unsanitary landfilling is 0.35 L/ton, based on official data, whereas a sanitary landfill uses 3 L/ton. Emissions of these fuels, used at landfills both for waste as well as residues, have been included also as landfill emissions. After generating these inventory data, we calculated the GWP impact category based IPCC model 2006 for a 100-year time horizon. Data of emission factors were obtained from the IDEA database of MILCA software. The following tables show detailed explanations of calculations for CH_4 emission in different scenarios.

Table S31. Model designed for calculation of CH_4 for the open dumping baseline scenario (S-0)

Parameter	Amount	Unit	Source
Waste amount deposited, HWDS	=0.43 × 2527 × 10^-3	Gg	calculation
Waste amount deposited, HWDS	1.08661	Gg	calculation
* Degradable organic carbon, DOC	= 0.74 × 0.15+ 0.05 × 0.4	Gg C/Gg	IPCC
* Degradable organic carbon, DOC	0.131	Gg C/Gg	IPCC
Methane correction factor, MCF	0.4	-	IPCC
Fraction of DOC under anerobic condition, DOC_F	0.77	-	IPCC
Methane generation in Landfill by volume, F	0.5		IPCC
Molecular weight ratio of CH4/C, used as conversions factor to change C to CH4	16/12		IPCC
Recovered methane, R	0	Gg	Assumed
Oxidation factor, OX	0		IPCC
CH_4 emissions	0.02922836	Gg	calculation
CH_4 emissions	29.23	ton	calculation

* DOC = % of food waste × 0.15 + % of paper waste × paper

Table S32. Model designed for calculation of CH_4 for unsanitary landfill of baseline scenario (S-0)

Parameter	Amount	Unit	Source
Waste amount deposited, HWDS	=0.525 × 2527 × 10^-3	Gg	calculation
Waste amount deposited, HWDS	1.326675	Gg	calculation
Degradable organic carbon, DOC	0.131	Gg C/Gg	IPCC
Methane correction factor, MCF	0.6	-	IPCC
Fraction of DOC under anerobic condition, DOC_F	0.77	-	IPCC

Methane generation in Landfill by volume, F	0.5		IPCC
Molecular weight ratio of CH_4/C, used as conversions factor to change C to CH_4	16/12		IPCC
Recovered methane, R	0	Gg	Assumed
Oxidation factor, OX	0		IPCC
CH_4 emissions	0.0535	Gg	calculation
CH_4 emissions	53.53	ton	calculation
Fuel consumption at unsanitary landfilling	0.35	L/ton	DoS
Total fuel consumption at unsanitary landfilling	=1.326675× 0.35 × 10^3	L	calculation
Total fuel consumption at unsanitary landfilling	459	L	calculation
* Change into energy	=36.9 × 459	MJ	calculation
Change into energy	16,946	MJ	calculation
Fuel consumption for treatment of residues after recycling process	=5.5 × 0.35	L	calculation
Fuel consumption for treatment of residues after recycling process	1.9	L	calculation
Change into energy	69.7	MJ	calculation
** Total energy	17,015	MJ	calculation

* Colorific Value (CV) of diesel = 36.9 MJ/L . ** Total energy means the summation of fuel energy used for dumping the waste and the residues after recycling left and go to landfill site.

Note: Tables A31 and 32 have given a bit more detail to make the calculations of the following table understandable.

Table S33. Model designed for calculation of CH_4 emissions for unsanitary landfill of S-1

Parameter	Amount	Unit	Source
Waste amount deposited, HWDS	2.527	Gg	calculation
Degradable organic carbon, DOC	0.131	Gg C/Gg	IPCC report
Methane correction factor, MCF	0.6	-	IPCC report
Fraction of DOC under anerobic condition, DOC_F	0.77	-	IPCC report
Methane generation in landfill by volume, F	0.5		IPCC
Molecular weight ratio of CH_4/C, used as conversion factor to change C to CH_4	16/12		
Recovered methane, R	0	Gg	Assumed
Oxidation factor, OX	0		IPCC

CH_4 emissions	0.101959396	Gg	calculation
CH_4 emissions	101.96	ton	calculation
Fuel consumption at unsanitary landfilling	0.35	L/ton	DoS
Total fuel consumption at unsanitary landfilling	884	L	calculation
Change into energy	32,636	MJ	calculation

Table S34. Model designed for calculating CH_4 emissions for unsanitary landfill of S-2

Parameter	Amount	Unit	Source
Waste amount deposited, HWDS	2.208598	Gg	calculation
Degradable organic carbon, DOC	0.111	Gg C/Gg	IPCC report
Methane correction factor, MCF	0.6		IPCC report
Fraction of DOC under anerobic condition, DOC_F	0.77		IPCC report
Methane generation in Landfill by volume, F	0.5		IPCC report
Molecular weight ratio of CH_4/C, used as conversions factor to change C to CH_4	12/44		IPCC report
Recovered methane, R	0	Gg	assumed
Oxidation factor, OX	0		IPCC
CH_4 emissions	0.076	Gg	literature
CH_4 emissions	76	ton	calculation
Fuel consumption at unsanitary landfilling	0.35	L/ton	DoS
Total fuel consumption at unsanitary landfilling	773	L	calculation
Change into energy	28524	MJ	calculation
Fuel consumption for treatment of residues after recycling process	=95.5 × 0.35	L	calculation
Fuel consumption for treatment of residues after recycling process	33.4	L	calculation
Fuel consumption for treatment of residues after recycling process	1,232.5	MJ	calculation
Total energy	29,756.46	MJ	calculation

Table S35. Model designed for calculating CH_4 emissions for unsanitary landfill of S-3

Parameter	Amount	Unit	Source
Waste amount deposited, HWDS	2.29957	Gg	calculation

Degradable organic carbon, DOC	0.121	Gg C/Gg	IPCC report
Methane correction factor, MCF	0.6		IPCC report
Fraction of DOC under anerobic condition, DOC_F	0.77		IPCC report
Methane generation in Landfill by volume, F	0.5		IPCC report
Molecular weight ratio of CH_4/C, used as conversions factor to change C to CH_4	12/44		IPCC report
Recovered methane, R	0	Gg	assumed
Oxidation factor, OX	0		IPCC
CH_4 emissions	0.085700375	Gg	calculation
CH_4 emissions	85.7	ton	calculation
Fuel consumption at unsanitary landfilling	0.35	L/ton	DoS
Total fuel consumption at unsanitary landfilling	804.85	L	calculation
Change into energy	29,698.95	MJ	calculation
Fuel consumption for residues treatment after recycling process	51.67	ton	calculation
Fuel consumption for residues treatment after recycling process	18.09	L	calculation
Change into energy	667.36	MJ	calculation
Total energy	30,366.29	MJ	calculation

Table S36. Model designed for calculating CH_4 emissions for unsanitary landfill of S-4

Parameter	Amount	Unit	Source
Waste amount deposited, HWDS	2.29957	Gg	calculation
Degradable organic carbon, DOC	0.121	Gg C/Gg	IPCC report
Methane correction factor, MCF	1	-	IPCC report
Fraction of DOC under anerobic condition, DOC_F	0.77	-	IPCC report
Methane generation in Landfill by volume, F	0.5		IPCC report
Molecular weight ratio of CH_4/C, used as conversions factor to change C to CH4	12/44		IPCC report
Recovered methane, R	0	Gg	assumed
Oxidation factor, OX	0		IPCC
CH_4 emissions	0.142833958	Gg	calculation
CH_4 emissions	142.8	ton	calculation

Fuel consumption at sanitary landfilling	3.00	L/ton	literature
Total fuel consumption at sanitary landfilling	6,898.71	L	calculation
Change into energy	254,562.39	MJ	calculation
Fuel consumption for residues treatment after recycling process	155.02	L	calculation
Energy	5,720.10	MJ	calculation
Total energy	260,282.5	MJ	calculation

Table S37. Estimating GHG emissions at a landfill site under different scenarios

Scenario	Impact category (CO_2eq)	Unit	Open dumping	Unsanitary landfilling	Sanitary landfilling
Baseline scenario	Global Warming	ton CO2 eq/year	267,910.00	488,947.67	-
Scenario 1			-	931,316.31	-
Scenario 2			-	689,842.28	-
Scenario 3			-	770,534.75	-
Scenario 4			-	-	1,308,513.88

(2) Cost

A. Estimating the number of workers

The current WMS has 36 workers working at the landfill site. They are able to landfill 52.71% (1,332 ton/day) of waste, including 52.5% of that which has been collected plus residues (0.21%) from reycling treatent. Therefore, a worker, on average, can treat 37 tons of waste per day at an unsanitary landfill of Kabul city. However, for a sanitary landfill, formalized workers have been assumed as fewer than a tenth in number compared with the number at an MRF. Because the number of formalized workers at an MRF has been calculated as 494. The equation of integration of informal workers at a landfill site is

$$A = X / A, \tag{36}$$

where A represents the number of informal workers to be integrated (number), X represents the amount of waste that is landfilled (ton/day), and A is the amount of waste treated per person per day (ton/person/day).

Table S38. Number of informal workers to be integrated at landfill site in different alternative scenarios (ton/day)

Scenario 1	33
Scenario 2	26
Scenario 3	27
Scenario 4	13

B. Cost calculation

The equation for calculation the cost at landfill site is

$$B = X \times CoL, \quad (37)$$

where B represents the total cost (ton/year), X signifies the amount of waste (ton/day), and CoL stands for the cost of landfill per ton of waste($/ton).

Table S39. Cost calculation of waste landfilling in different scenarios of WMS ($/year)

Scenario	Amount of waste (ton/day),X	Unit cost ($/ton), CoL	Total cost (ton/year)
Baseline scenario	1,331.73	[a]1.60	777,729.74
Scenario 1	2,527.00	1.60	1,475,768.00
Scenario 2	2,304.12	1.60	1,345,605.26
Scenario 3	2,351.63	1.60	1,373,349.70
Scenario 4	2,351.63	[b]10.00	8,583,435.63

Sources: [a] Department of sanitation (2020) [b] Global study for purpose of global world bank guidance development solid waste management holistic decision modeling (2008).

Section 4. Power generation

The electricity mix grid of Kabul city consists of energy produced from domestic resources (40%), and imported resources from Uzbekistan (60%), according to Da Afghanistan Breshna Sherkat (DABS). Table A40 presents the electric energy sources and their contributions in Kabul city. In addition, the unit price of electricity in commercial and industrial zones is $ 0.16/kWh.

Table S40. Electricity grid mix of Kabul city

Sources of energy	Amount in %
[a] Energy from domestic resources	
Hydroelectric power	62
Heavy oil	38
	60
[B] Imported energy	
Natural gas	86.12
Coal	6.20
Heavy oil	1.05

Hydroelectric power	6.63
Total	
Natural gas	51.67
Coal	3.72
Heavy oil	15.90
Hydroelectric power	28.79

Source: [a] DABS (2020) [b] IDEA database

(1) Greenhouse gas emissions

The GHG emissions from electricity consumption have been integrated with diesel fuel emissions at the section of recycling treatment, where we use electric energy. To calculate GHG releases, we applied the IDEA database after generating basic data (see MRF/recycling).

(2) Cost

Electricity cost calculations were conducted in the section of MRF/recycling, as the price of each kilowatt hour in commercial and industrial zones as $0.16 [DABS, 2020].