Building Integrated Agriculture Simulation (BIA-SIM)

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Agriculture consumes 30% of the world's fossil fuels and 70% of freshwater. About one third of all greenhouse gas emissions come from the Built Environment, and uses about 20% of total energy. Urban Agriculture promises to minimize food and water waste utilizing Building Performance Simulation (BPS) tools that assess crop yields, water usage and energy needs for Building Integrated Agriculture (BIA). However, BIA may attain better efficiencies if agriculture and buildings share their waste products. Here, we introduce Building Integrated Agriculture Simulation (BIA-SIM), a framework for software that visualizes and quantifies early-stage design outcomes of BIA that combines circular waste flows of building and farm. Users can determine which resources - food, water, air, and energy - are most important to co-optimize based on their ecological and economic concerns. BIA-SIM user input includes location, 3D site model, site and building details, number of occupants, farm type and crops. Greywater, CO2 from occupants and building energy usage are calculated. Outputs demonstrate how a software framework informed by an extensive database of plants, their properties and their farming requirements can be utilized to identify, design and exploit feedback loops between building and urban agriculture waste products. To demonstrate several use scenarios, a site in New Delhi, India was chosen for an urban agriculture-integrated residential building. In one example, using 60% of building grey water for irrigation of tomato, we found 47% of the maximum buildable surface area would be needed for tomato production. More than 100% of the CO2 emitted by building occupants could be absorbed, and the plants' thermal mass could save 50% of cooling energy using farm layouts that, in turn, enhanced food output based on solar exposure. Several other scenarios will be shown that demonstrate the broader benefits urban agriculture can have for the built environment beyond food production.

Introduction

The world population is quickly increasing, outpacing the expansion of agricultural production, resulting in a food security crisis. World population is expected to exceed 9 billion people by 2050, with cities housing more than 70% of the population (World population prospects 2019: Highlights 2019). The World Bank defines food security as "access by all people at all times to enough food for an active, healthy life" (World development report, 1986). According to the Food and Agricultural Organization (FAO) of the United Nations (UN), "food security exists when all people at all times have access to sufficient and nutritious food to meet the dietary needs and food preference for an active and healthy life."

In the long run, sustainable food security is critical. The current rate of urbanization is accompanied by increases in urban poverty and food insecurity. The combination of population growth, rapid urbanization, and climate change poses a significant threat to food supply. Food systems are part of intricate worldwide networks of agriculture, processing, storage, and distribution, making them particularly vulnerable to geopolitical, economic, or natural disaster-related catastrophes . Food consumed in cities is not only transported over longer distances, creating worries about "Food Miles" greenhouse gas (GHG) emissions, but an estimated one-third of world food production is lost or wasted in the process (Gustavsson et al., 2011).

Building Performance Simulation (BPS) tools have demonstrated by a number of studies to have a significant promise for enhancing the energy efficiency of agricultural production facilities. Over the course of the last few years, climate-based simulations with integrated plant growth models have been built within ESP-r, TRNSYS, and Energy Plus in order to evaluate the thermal behavior of agricultural greenhouses (Alvarez- Sánchez et al., 2014; Carlini & Castellucci, 2010; Marucci et al., 2013), as well as evaluate passive design strategies such as natural ventilation (Mashonjowa et al., 2013), and adaptive shells (Ward et al., 2015). Although earlier Building Integrated Agriculture studies that made use of BPS tools took into consideration lighting, climate control, passive systems, or water consumption individually, there is currently no operational tool that integrates all these parameters into a single workflow that enables the user to evaluate a BIA project in a manner that is comprehensive. It is essential to integrate these sub-models because they frequently have an effect on one another. For instance, supplemental artificial lighting

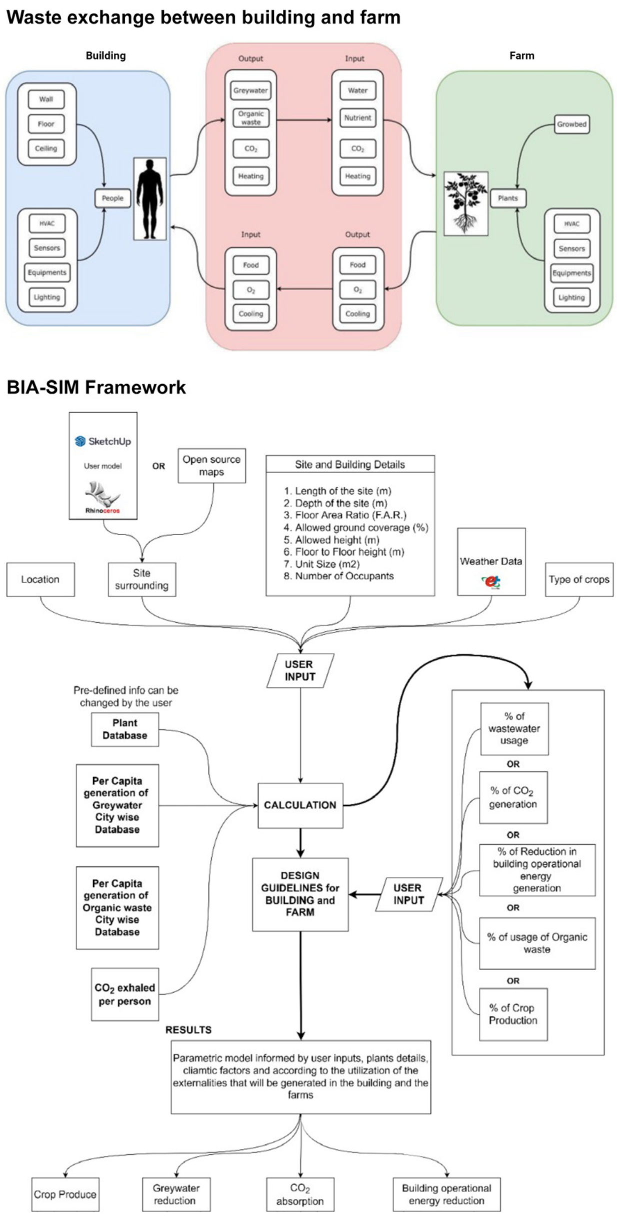

Figure 1. The outputs of building and farm, including greywater, food, heating, cooling, CO2 and oxygenated air, are designed for productive exchange within the BIA-SIM framework

provides plants with optimal growing conditions; however, the contribution of heat from lighting systems to the overall heating requirements of a farm can be significant (Dorais, 2003). In addition, to typical rural ground-based greenhouses, BIA urban farms have to be planned in accordance with urban context-related restrictions. These constraints might include structural load limits, a restricted rooftop area, the orientation of the host building, or shadings from nearby structures.

As a result, the primary objective of this paper is to present a framework for simulation-based analysis software that would enable the quantification of the broader environmental feedback loops of BIA in apartment buildings situated in urban environments. Furthermore, this framework creates design guidelines for the integration of agriculture farms in buildings in a way so that the waste products like greywater or CO2 of one system and be used as the supplements for the other . We demonstrate the utility of the framework on a case study building for New Delhi, to demonstrate the potential impact that Building Integrated Architecture Simulation (BIA-SIM) can have during the design process. The procedure that follows is based on climatic data, crop needs, and the geometry of both the building, the farm and the surroundings. This framework is developed to help architects and urban planners to examine the advantages of BIA for a specific site, which would help motivate the adoption of a new, more sustainable and economical typology of building system.

Research methods

Building Integrated Agriculture Simulation (BIA-SIM) is an architectural design tool that can use to develop design guidelines and parametric models of buildings integrating agriculture, which are guided by the waste products of the building and the agriculture system. This tool considers greenhouses and indoor conditioned farms, as well as soil and soilless cultivation techniques, in the presence of both natural and artificial illumination. Greenhouses affixed to rooftops and facades, as well as farms with controlled environments, make up these farms. BIA-SIM focuses on simulating:

1. The optimized balance between greywater generated by building occupants to water required by crops.

2. The absorption of CO2 by crops to the CO2 exhaled by building occupants.

3. The reduction of building operational energy consumption due to the integration of the farms in the building.

Creating a Plant Database

To successfully cultivate vegetable plants inside the building, the characteristics and requirements of the Plants needed to be catalogued are organized in a Plant database. It has been found during this study that although there is much research going on in the field of plants and agriculture, there are not many resources where information on plants can be found. So, this database in the future can also grow in to one such resource where detailed information about the characteristics of all plants can be found . During this investigation, the tomato plant will serve as the crop.

Creating a database for greywater production per capita for Major cities

More than 80% of the greywater generated in cities is dumped untreated into the environment (The United Nations World Water Development Report, 2022). The quantity of greywater generated on a daily basis per capita in a city is available through city municipality resources and scholarly studies. However, this information is not readily available and it is difficult to access comprehensive data about the greywater generation of various cities. Therefore, a database is created where the amount of greywater generated per capita per day for different cities in the world can be recorded.

For this study the cities of India are taken as examples.

User inputs for BIA-SIM

As the framework for the software is being developed, an architect (myself) has also become its first user. The software will take an EPW weather file and the location into consideration. This is where the residential apartment is going to be built. The 3D model of the location and its surroundings can be imported from open source maps; however, there is a lack of information in open sources, such as a lack of 3D outlines for many cites. When this occurs, the user will be tasked with developing the site and the geometry that surrounds it using 3D applications such as Rhinoceros 3D/Sketch-up, amongst others.

For the purpose of demonstration, a site has been chosen in New Delhi, India.

The EPW weather data file can be imported from the Energyplus website https://energyplus.net/

The number of occupants and the size of each of the many types of apartment typology are both predetermined, but subsequent adjustments are possible as the building uses simple, consistent volumes that can be combined into apartment units and farms of different sizes

One Bedroom + Hall + Kitchen (BHK), 50 m2 can accommodate up to 2 people, two BHK, 75 m2 can accommodate up to 4 people and three BHK, 100 m2 can accommodate up to 5 people. These characteristics allow for the determination of a given volume or floor area, as well as the number of different apartment typologies.

Optimization of greywater

The quantity of greywater generated daily per person in the city where the building is to be constructed is selected from the database available. If it is not present or if the user has more accurate information about the greywater generation in the city, then they can enter their own value. In this case, the data of New Delhi is taken from the database. The software then asks the user to choose the percentage of greywater generated in the building to be used in the farms. With the user input, the software then computes the total volume of water in liters and the number of plants required to absorb the amount of greywater chosen by the user which, finally, gives the surface area of the farms. The water requirement for the plants (here the Tomato plant) is calculated with the help of the Penman-Monteith Evapotranspiration equation (Zotarelli et al).

Site and Building Inputs	
Length of the Site (m)	60
Width (m)	80
Floor Area Ratio (F.A.R.)	2
Allowed Ground Coverage (%)	30
Allowed Height (m)	30
Floor to Floor Height (m)	3
Unit Size (m2)	100
Number of Occupants	5
Percentage of Greywater use	**60**

Building and People Calculation	
Site Area (m")	4800
Total builtup Area (m2)	9600
Total builtup Area (m')	9600
Allowed Area (m")	1440
Total number of Floors	7
Total number of Units	51
Total Number of Occupants	256
Total amount of Wastewater (Lt/day)	44800
Surface area occupied by 1 person (m2)	38
Water Used Farm	26880

Plants Calculation	
Evapotranspiration Eto	6
Plant water in 1 in2	4.98
Number of Plants per m'	4
Surface area for Farm	4480
Percentage for Farm Area	**47**

Outputs	
Surface Area for Occupants	5120
Percentage for Occupant area	**53**
Average Total Leaf Surface Area of 1 plant (m2)	133.45
Number of Plants	17,920
Total area of leaf surface (m2)	2,391,424
Total g CO2/day absorbed	2,391,424
Number of People	256
Total g CO2/day produced	214,272

Figure 3. Showing the inputs and the calculations done by BIA-SIM and the percentage of greywater usage in the farms which the user is required to set in order for BIA-SIM to calculate the amount of farm surface area. Here the user has chosen 60% of Greywater use

Using 60% of the greywater generated in the building

Percentage of Livable area = 53%, Area = 5,120m2, Percentage of Farm area = 47%, Area = 4,480m2

The program is set to plot the 47% of the farm areas on/in the building that receive more than 5 hours of sunlight

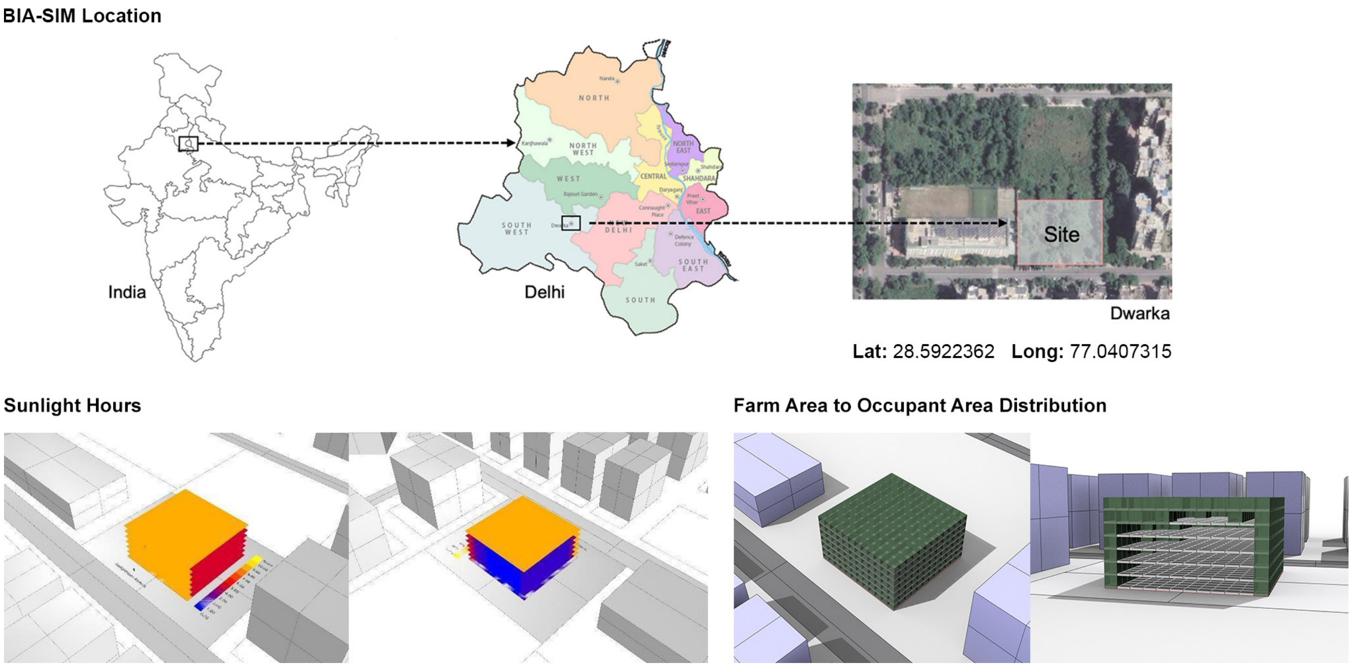

Figure 3. Site selection and building orientation informs a daylight analysis by which BIA-SIM optimizes the distribution of farm and occupant volumes in the building. In this example, the user chose 60% greywater to be reused for farming. BIA-SIM calculated the number of viable farm volumes and arranged them so that they receive maximum sun light hours

Air exchange (amount CO2 exhaled by people to the amount of CO2 absorbed by plants)

After the percentage of greywater reuse is fixed by the user then BIA-SIM starts the calculation for the amount of CO2 exhaled by the people in the building to the amount of CO2 absorbed by the plants (here the Tomato plants) in the farms integrated in the building. +

In this scenario, the first calculation is when 100% greywater of the building is reused.

Reduction in Building Operational energy with the help of agricultural farms

Consumption of energy by urban systems is a key issue that has to be addressed for sustainable development. This section's goal is to provide a solution to the following question: what would the overall yearly energy savings be because of having agricultural integration in residential buildings?

Initially, BIA-SIM computed the yearly energy consumption of a single-family unit consisting of a living room, dining room, kitchen, two bedrooms, and two bathrooms, determining the U-values and values of the walls, roof, and windows based on their general characteristics (U-values for common materials, n.d.).

In the following step of the computation, it was considered that the unit has agriculture farms on its south facing façade as well as on its roof; hence, the U-values of plants were added to the U-values of the brick wall, concrete roof, and glass (Muñoz-Liesa et al., 2020).

BIA-SIM performed the calculations necessary to determine the yearly energy consumption and generated a graph illustrating the operational energy reduction because of the utilization of the agricultural farms.

Furthermore, it is able to simulate the Useful Daylight Illuminance (UDI) within the unit, which will assist the user in assessing whether the farm is interrupting with the essential quantity of daylight required inside the apartment.

Results of reduction in glare produced by direct sunlight that falls inside the apartment, which enables the user to determine the placement of the agricultural farm.

Food Production

The goal of this research is not focused on whether Building Integrated Agriculture in a residential building that is located in an urban setting is capable of meeting the nutritional requirements of the people who live in those buildings, yet to make an argument, a literature study was done to find out whether it can theoretically support the occupants of the building or not.

When 60% of the greywater generated by the building is utilized in the agricultural production of tomatoes, the agricultural farm

Energy Use Intensity (EUI): Normal building

Space Shape	
Space Length [ft]	33
Space Width [ft]	33
Space Height [ft]	10
South Window [ft^2]	132
Constructions	
Wall U [Btu/ft^2-F]	2.00
Roof U [Btu/ft^2-F]	2.00
Window U [Btu/ft^2-F]	0.12
Window SHGC [%]	0.2
Internal Loads	
LPD [W/ft^2]	0.5
EPD [W/ft^2]	1
Occupancy Parameters	
Ocucpants [#pp]	5
Occupant Gains [W/pp]	500
Ventilation Parameters	
OA Flowrate [cfm/pp]	10
Conditioning Parameters	
Winter Tin [F]	72
Summer Tin [F]	75
System Parameters	
Heating COP	1
Cooling COP	5

Peak Calcs	Heating	Cooling
T_{out} [F]	58	92
I_{south} [Btu/ft^2]	0	50
Infiltration [cfm/ft2]	0.04	0.04
Peak Calcs [Btu/hr]	**Winter**	**Summer**
Q_{walls}	(33,264)	40,392
Q_{roof}	(30,492)	37,026
Q_{window}	(222)	269
$Q_{infiltration}$	(659)	800
$Q_{ventilation}$	(756)	918
Q_{losses}	**(65,392)**	**79,405**
Q_{solar}	-	1,320
Q_{lights}	1,858	1,858
$Q_{equipment}$	3,716	3,716
$Q_{occupants}$	8,530	8,530
Q_{gains}	**14,104**	**15,424**
Net Peak [Btu/hr]	**(51,289)**	**94,829**

Degree Day Calcs		Heating	Cooling
$T_{Balance\ Point}$ [F]		69	72
DD Calc	Avg Tout	HDD	CDD
Jan	58	-329	-411
Feb	62	-209	-291
Mar	73	121	39
Apr	84	451	369
May	91	661	579
Jun	92	691	609
Jul	87	541	459
Aug	86	511	429
Sep	85	481	399
Oct	78	271	189
Nov	69	1	-81
Dec	60	-269	-351
Degree Days [F-hr/yr]		**-808**	**3072**

Demand Calcs	Heating	Cooling	
I_{south} [kBtu/ft^2-yr]	180	180	
Period [# Days]	90	240	
Util./Diversity [%]	0.5	0.5	
Demand [kBtu/hr]	**Heating**	**Cooling**	**Electricity**
Q_{walls}	(46,090)	1,75,206	
Q_{roof}	(42,249)	1,60,605	
Q_{window}	(307)	1,168	
$Q_{infiltration}$	(913)	3,469	
$Q_{ventilation}$	(1,047)	3,982	
Q_{losses}	**(90,606)**	**3,44,430**	
Q_{solar}	586	1,562	
Q_{lights}	2,006	5,351	8,137
$Q_{equipment}$	4,013	10,701	16,275
$Q_{occupants}$	9,212	24,566	
Q_{gains}	**15,818**	**42,180**	
Demand [kBtu/yr]	**(74,788)**	**3,86,611**	**24,412**

$Q_{Conduction} = U_{assembly} \times A_{surface} \times (T_{out} - T_{in})$
$Q_{solar} = SHGC_{average} \times A_{window} \times I_{total}$
$Q_{infiltration} = 1.08 \times CFM \times (T_{out} - T_{in})$
Q_{lights} = LPD x Floor Area
$Q_{equipment}$ = EPD x Floor Area
$Q_{occupants}$ = #pp x Heat Gain/pp
$Q_{ventilation} = 1.08 \times CFM \times (T_{out} - T_{in})$

Balance Point Temperature is T_{out} when $Q_{gains} + Q_{losses} = 0$

For Demand Calculations use $HDD_{balance\ point}$ X 24 (hrs/day) instead of $(T_{out}-T_{in})$

1W = 3.412 Btu/hr

	Heating	Cooling	Electricity
TEDI [kBTU/ft^2-yr]	69	355	
EUI [kBTU/ft^2-yr]	69	71	61
Project EUI [kBtu/ft^2/yr]			**201**

EUI: Farm on building facade and roof

Space Shape	
Space Length [ft]	33
Space Width [ft]	33
Space Height [ft]	10
South Window [ft^2]	132
Constructions	
Wall U [Btu/ft^2-F]	0.15
Roof U [Btu/ft^2-F]	0.15
Window U [Btu/ft^2-F]	0.12
Window SHGC [%]	0.2
Internal Loads	
LPD [W/ft^2]	0.5
EPD [W/ft^2]	1
Occupancy Parameters	
Ocucpants [#pp]	5
Occupant Gains [W/pp]	500
Ventilation Parameters	
OA Flowrate [cfm/pp]	10
Conditioning Parameters	
Winter Tin [F]	72
Summer Tin [F]	75
System Parameters	
Heating COP	1
Cooling COP	5

Peak Calcs	Heating	Cooling
T_{out} [F]	58	92
I_{south} [Btu/ft^2]	0	50
Infiltration [cfm/ft2]	0.04	0.04
Peak Calcs [Btu/hr]	**Winter**	**Summer**
Q_{walls}	(2,495)	3,029
Q_{roof}	(2,287)	2,777
Q_{window}	(222)	269
$Q_{infiltration}$	(659)	800
$Q_{ventilation}$	(756)	918
Q_{losses}	**(6,418)**	**7,793**
Q_{solar}	-	1,320
Q_{lights}	1,858	1,858
$Q_{equipment}$	3,716	3,716
$Q_{occupants}$	8,530	8,530
Q_{gains}	**14,104**	**15,424**
Net Peak [Btu/hr]	**7,685**	**23,217**

Degree Day Calcs		Heating	Cooling
$T_{Balance\ Point}$ [F]		41	41
DD Calc	Avg Tout	HDD	CDD
Jan	58	503	499
Feb	62	623	619
Mar	73	953	949
Apr	84	1283	1279
May	91	1493	1489
Jun	92	1523	1519
Jul	87	1373	1369
Aug	86	1343	1339
Sep	85	1313	1309
Oct	78	1103	1099
Nov	69	833	829
Dec	60	563	559
Degree Days [F-hr/yr]		**0**	**12862**

Demand Calcs	Heating	Cooling	
I_{south} [kBtu/ft^2-yr]	180	180	
Period [# Days]	0	360	
Util./Diversity [%]	0.5	0.5	
Demand [kBtu/hr]	**Heating**	**Cooling**	**Electricity**
Q_{walls}	-	55,007	
Q_{roof}	-	50,423	
Q_{window}	-	4,890	
$Q_{infiltration}$	-	14,522	
$Q_{ventilation}$	-	16,669	
Q_{losses}	**-**	**1,41,511**	
Q_{solar}	-	2,343	
Q_{lights}	-	8,026	8,137
$Q_{equipment}$	-	16,052	16,275
$Q_{occupants}$	-	36,850	
Q_{gains}	**-**	**63,271**	
Demand [kBtu/yr]	**-**	**2,04,781**	**24,412**

$Q_{Conduction} = U_{assembly} \times A_{surface} \times (T_{out} - T_{in})$
$Q_{solar} = SHGC_{average} \times A_{window} \times I_{total}$
$Q_{infiltration} = 1.08 \times CFM \times (T_{out} - T_{in})$
Q_{lights} = LPD x Floor Area
$Q_{equipment}$ = EPD x Floor Area
$Q_{occupants}$ = #pp x Heat Gain/pp
$Q_{ventilation} = 1.08 \times CFM \times (T_{out} - T_{in})$

Balance Point Temperature is T_{out} when $Q_{gains} + Q_{losses} = 0$

For Demand Calculations use $HDD_{balance\ point}$ X 24 (hrs/day) instead of $(T_{out}-T_{in})$

1W = 3.412 Btu/hr

	Heating	Cooling	Electricity
TEDI [kBTU/ft^2-yr]	-	188	
EUI [kBTU/ft^2-yr]	-	38	61
Project EUI [kBtu/ft^2/yr]			**99**

Figure 4. Energy Use Intensity (EUI) analysis comparing an apartment unit in New Delhi , India without farms and with farms on the building facade and roof. The shading provided by farm integration reduces the apartment's EUI by over 50% from 201 kBtu/ft^2/yr to 99

has a total area of 4,480 m2, and the number of tomato plants is 17,920. The total area for occupants is 5,120 m2, and there are 256 people using that space. Then the production of tomatoes will be roughly 448,000 kg/year (Meet demand with better Tomatoes, n.d.). Here the consumption of tomatoes by the occupants of the building will be approximately 5,200 kg/year as the number of occupant increased. Similar to case one, this result also suggests that the farms can satisfy the requirements of the occupant of the building and also cater to the markets.

When 30% of the total amount of greywater created in the building is utilized in the production of tomatoes for agricultural purposes, the production of tomatoes is roughly 292,200 kg/year and the occupants will consume around 6,680 kg/year. Thus, all the scenarios show that by using the greywater of the building satisfactory food production can also be achieved .

Conclusion

This research has presented a novel approach to integrating BIA to buildings with the help of a simulation tool (BIA-SIM). Results indicate that this software can reliably give results for optimization of greywater, calculation of absorption of the carbon-dioxide that is exhaled by the occupants of the building and also calculate the reduction of building operational energy due to the integration of agriculture into the building. New methods were developed to help the user to optimize certain parameters like choosing between farm area and human area. Analysis showed that there would be less waste of resources, e.g., water, energy in the building if agriculture is integrated and other factors like temperature and light can be managed effectively using both natural and artificial lighting.

This tool differs from existing approaches in that it can be used in the designing stages of a building to check the viability of integrating agriculture in a residential building. This software shows the benefits of using BIA for other goals than just production of crops such as grey water remediation and building energy reduction.

Future work will entail the detailed development of the software, testing and validation of more complex geometries, adding more plants to the database and more databases in general like cities regulations, 3D maps of cites etc. to name a few. It will include other options of recyclable products like organic waste, oxygen produced by the plant etc. It will have a carbon footprint calculator that would determine the viability of the BIA. Furthermore, the software will be able to choose and optimize between the resources/waste products and give a balance prediction. This type of tool can help us in creating a better way of living in the future. With this tool, people can balance their requirements whether they need more food or more clean air or whether they need to recycle more greywater. It will help us in creating autonomous, self-reliant communities.

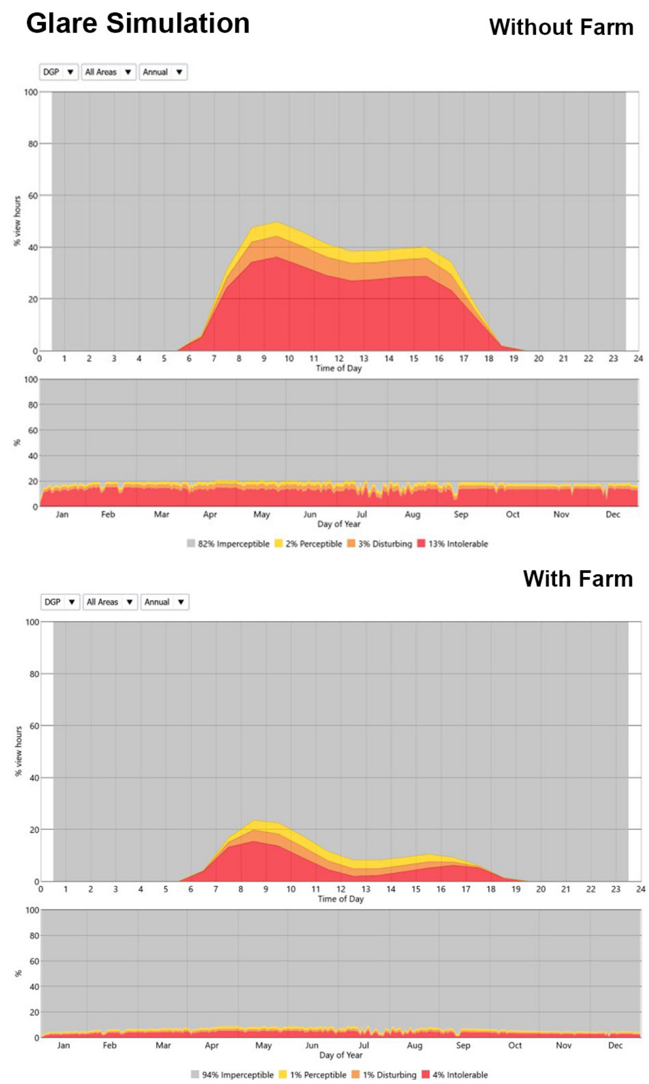

Figure 5. Glare simulation inside the New Dehli apartment with and without the farm. Glare is reduced by over 50% with the farm

PAPER

ENDNOTES

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