End-to-End Decentralized Tracking of Carbon Footprint using Internet of Things and Distributed Databases

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***Abstract*—Environmental impact of food supply chains such as the meat chain, particularly in terms of deforestation, water depletion, and greenhouse gas emissions, is significant. The modern meat supply chain, which includes stages such as feed harvesting, processing, shipment, and retail, often lacks vertical integration, making it challenging to precisely track and record carbon footprint for each packaged product. This issue arises from the absence of a unified platform to validate carbon emissions according to regulatory and scientific standards. To address this, we propose a decentralized blockchain-based framework set up by integrating IoTs and databases in a decentralized way to capture detailed carbon emissions throughout the chain, including transportation, feed harvesting, and waste management. The framework allows building flexible local and global collaboration groups for fine-grained emission tracking while ensuring privacy and transparency. It also facilitates integrating diverse information sources such as data streams, feeds, static and hybrid databases. The proposed system uses a blockchain and IoT infrastructure for secure data capturing and propagation, allowing participants to communicate policies and decisions related to carbon emissions. This extensible framework facilitates reliable traceability and can be scaled to track environmental data while incorporating feedback from regulators. The framework aims to provide a flexible, comprehensive and decentralized solution that is a collaborative effort to record, monitor, and regulate the carbon footprint across complex supply chains, promoting emissions reduction and management.**

***Index Terms*—Blockchain, carbon footprint, decentralized, food supply chain, Internet of Things**

I. INTRODUCTION

Amid rising global concerns about climate change, significant actions are being taken to promote efforts towards achieving net-zero Greenhouse Gas (GHG) emissions by 2050. China has set a goal for carbon neutrality by 2060, the USA has recommitted itself to the Paris Agreement, and over 60 countries have joined the EU's efforts to reduce global warming to 55% by 2050 [1]. However, accurately tracking detailed carbon footprints from major GHG emission sources remains a challenge, especially in complex supply chains that incorporate numerous independent processes such as production, packaging, shipment, and retail with little to no vertical integration or data sharing among participants. Using a central database to extract statistics from data owned by different organizations is not feasible due to significant privacy concerns, as well as the burden of database maintenance.

Quantifying carbon footprints has become increasingly important due to its critical role in global warming. Carbon footprints, part of the broader 'footprint family' that includes ecological, energy, and water footprints, encompass direct and indirect Carbon Dioxide CO_2 equivalent (CO_2eq) emissions from any system, process, or activity over a product's lifecycle. For well-defined system, carbon footprint is calculated using Lifecycle Assessment Method (LCA), considering emissions from raw material use to final disposal of product. Carbon footprint is quantified in CO_2eq units over a 100-year Global Warming Potential (GWP100) scale. For example, methane (CH_4) has a GWP of 25, and nitrous oxide (N_2O) has a GWP of 265, meaning that 1 part of CH_4 and 1 part of N_2O is equivalent to the emission of 25 parts and 265 parts of CO_2 respectively. Formally, carbon emissions are calculated as [2]:

$$E = A * EF(*GWP), \tag{1}$$

where E is emission in kg CO_2, A is activity that generates emissions in units of mass, volume or energy. EF is the emission factor in kg CO_2eq per mass, volume or energy unit and GWP is Global Warming Potential in kg CO_2eq.

The lifecycle of food products, particularly meat, greatly contributes to environmental degradation due to complex subsystems at each stage, such as pesticide use, refrigeration, and food disposal. The agricultural sector alone contributes 29% of all GHG, with CH_4 being a major component alongside CO_2 and N_2O. Livestock production, especially cattle raising, is a significant source of CH_4 emissions during feeding and breeding. Land management and deforestation from grazing further add to emissions. Emissions from supply chain activities are calculable at a fine-grained level but the lack of management platforms not controlled by any single organization is a major hurdle [3, 4]. Another difficulty in tracking emissions comes from the increasing global demand for animal protein that has led to more complex supply chain processes and layout.

The particular case of the beef supply chain which involves livestock management, feed harvesting, meat processing, cold storage, transportation, and retail, is important since all its stages are major GHG emitters. Hence, tracking and managing emissions from 'farm-to-fork' is challenging due to the independence of organizations, as well as the lack of (i) technology to seamlessly identify, record and share data from potential emission sources, and (ii) a decentralized and scalable regulatory management framework allowing independent organizations to connect and collaborate [5].

In this paper, we present a decentralized collaboration framework using blockchain and distributed databases that can be formed at will to include varying numbers of organizations to allow tracking carbon emissions locally or globally. The flexibility to scale decentralized groups without disruption allows for automating comprehensive tracking of data originating from carbon-emitting sources throughout the chain. Controlled carbon information is subsequently harnessed by a federated entity (e.g. regulator) that dynamically manages carbon conversion parameters agreed upon by participants. Prior work on end-to-end carbon emission calculations for disjoint supply chains either relied on central databases for integrating required data from disparate participants with numerous assumptions, or focused on a restricted portion of the chain for their analyses. Our proposed collaboration framework enables mutual tracking, management, and regulation of emissions in a secure manner. It facilitates the formation of local or global emission group zones. Further benefits include the ability to develop and share sequestration solutions, as well as the federation and validation of green projects.

II. Related Work

Most studies on the beef supply chain's carbon footprint use LCA but include only a subset of participants. They lack a comprehensive framework for detailed emission tracking [6, 7, 8]. Environmental impacts in supply chains have been studied using mix of LCA methods, which quantify emissions and resource consumption relative to system output [9]. For beef supply chains, LCA can calculate carbon footprints and other impacts (e.g., energy use, GWP) at each stage, but disconnectivity between participants hampers tracking changes and aggregated environmental effects. In addition to GHG protocols, standards like ISO 14040, 14044, 14046, 14064, and 14067 govern LCA methods, with bodies such as PAS 2050, IDF, IPCC, and FAO offer guidelines for quantifying carbon emissions [2, 5]. LCA is considered valuable for analyzing environmental impacts from resource use while IPCC's tiered guidelines have been among the most widely adopted tools for calculating emissions. IPCC tier level 1 uses fixed emission factors for basic calculations, while tier levels 2 and 3 employ more detailed, region-specific data respectively, to account for factors like fuel quality [10]. Tiers 1 and 2 also include trend assessments to identify significant emission variations over time. In our emissions framework, we use LCA parameters reported from tier 2 & 3 measures to account for indirect emissions from upstream suppliers and from processes involving use of raw materials. Combining LCA with a decentralized and distributed framework of blockchain and IoT network provides an efficient emission tracking application compared to other architectures such as the ones described in [11] due to real time granular data collection, transparency, data integrity, decentralization and user trust. Our proposed framework address the limitations of green IoTs and strengthens its use by providing real-time verifiable sustainable reporting, enhancing scalability and interoperability, leveraging user-controlled automation and accounting for data integrity and trust.

Recent literature highlights a blockchain's prominence as ledger system for supply chains but notes its vulnerabilities to security breaches, particularly in data components like off-chain databases and IoT devices [12, 13, 14, 15, 16, 17, 18]. Intelligently integrating IoTs with other interfaces for collecting, storing or sharing data across supply chain is crucial for timely reporting or extraction of emissions information. While blockchain and IoT adoption in consumable supply chains aims to enhance transparency, reliable data collection, deter tampering, simplify tracking, improve transportation, and incentivize participants, no single solution addresses all these aspects comprehensively [14, 19, 20, 21, 22, 23]. Some of the work use a central authority, or direct integration of interfaces to connect massive data sources. They adopt permissionless architectures and non-flexible IoT and blockchain frameworks that result in only some parts of the chain being able to connect and share mutually beneficial information.

The existing state-of-the-art methods for carbon footprint monitoring in agri-food production has been summarized by Camel et al. [24]. The discussed platforms aim to facilitate the logging of emissions from agri-chains using blockchain in addition to determining their economic impact. Majority of the described work rely on adoption of technology by all of the stakeholders and therefore are not completely decentralized and distributed because removing any random participant from the framework results in end-to-end disconnectivity and system disruption. The closest solution to our work is the application proposed by Hasan et al. [25]. The application utilizes a public ledger, relies on blockchain and cloud resources maintained by 3^{rd} party, focuses on data from only some of the participants, e.g. farmers, instead of involving end-to-end stakeholders and does not account for disruptions from participants leaving at any random instant. In contrast, our work focuses on utilizing a user-driven platform that is not disrupted by increasing number of active users, or abruptly leaving participants, making it truly distributed and decentralized. We use open-source tools to provide fully customizable private blockchain and IoT platforms that can be adapted to different scenarios and fully controlled by participating organizations with minimum reliance on 3^{rd} party.

Today's food supply chains produce 13.7 billion metric tons of CO_2eq, about 26% of anthropogenic emissions, contribute to terrestrial acidification (32%), eutrophication (78%), and occupy 43% of arable land, using 87% for food and causing 90% of global water scarcity. Unaccounted large-scale cattle raising in the beef supply chain leads to significant deforestation, land degradation, and water loss, contributing 61% of food-related GHG emissions and 18% of total GHG gases, with disconnected stakeholders making accountability difficult [26]. The modern beef supply chain includes complex subsystems from livestock management and feed harvesting to meat processing, cold storage, transportation, and retail, starting with calf rearing, followed by grain-fed breeding, and ending with beef distribution [26]. For our framework, we consider a beef supply chain network which includes farmer, breeder, processor, distributor, retailer, and consumer, with a

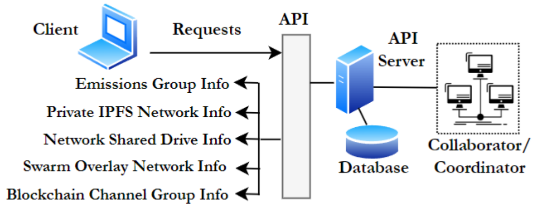


Fig. 1: A RESTful coordinator allows groups to start as root leaves, detach and expand by starting their own coordinator.

regulator overseeing tasks, allowing for variable distances and additional intermediaries to capture extensive scenarios. The environmental impact of the beef supply chain is evaluated using a end-to-end method, including all possible participants, with a focus on the carbon footprint of 1 pound of various beef cuts. Calculation of a beef supply chain's lifecycle inventory for carbon emissions is done by defining standard variables that represent different processes at each organization.

III. Proposed Framework and Implementation

We implement the supply chain collaboration framework for emissions tracking with four key requirements. It must be: (i) generic, (ii) scalable, (iii) data-driven, and (iv) reliable. A *generic* framework allows seamless participation and flexible group formation. A *scalable* framework supports modular and decentralized formations. A *data-driven* framework ensures reliable emissions data storage, retrieval, and dissemination over end-to-end channels. A *reliable* framework guarantees secure, disruption-free, and privacy-preserving communication. The proposed framework is designed to be reconfigurable for different emissions applications with participant consensus. These requirements are the basis for a secure, privacy-preserving platform for tracking emissions that enhances trust, traceability, and transparency in supply chains, particularly benefiting food supply chain operations without being invasive.

The core of our framework is the underlying permissioned blockchain structure (as shown in Fig. 2) that seamlessly integrates with IoTs and distributed databases along with network elements required for connectivity. This structure includes participants (e.g., farmers, processors) forming connected consortium groups. In our framework, "organization" refers to supply chain participants with unique goals, "consortium" denotes a collection of organizations or participants with shared goals, "group" is a subset within an organization with common objectives and "participant" refers to an individual user or a organizational formation utilizing the connectivity framework. Each group records emission-driven data from processes on digital ledgers, storing pointers to vital information on the blockchain for internal or external sharing. Information sharing and communication are enabled through controlled channels, networks, interfaces, and shared databases.

A. Coordinator as staring collaboration point

A coordinator (collaborator) is used as a starting point initially to coordinate group formation and resource pooling, while the organizations create and upload group related network resources (as shown in Fig. 1). All resources needed

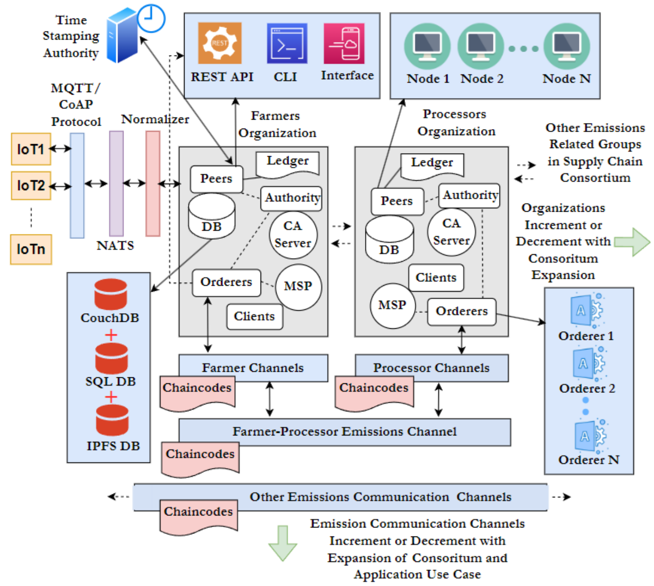


Fig. 2: Major components of the collaboration framework include Peer, Database (DB), Certificate Authority (CA), Internet of Things (IoTs) and connectivity channels.

to start databases, IoTs and blockchain infrastructure are provided as containerized applications (Docker Containers). The starting collaborator starts the basic blockchain infrastructure consisting of a 'manager' with a starting blockchain channel 'emissions-channel' to which other groups initially connect. Then, members create their own custom channels with other members by forming groups at the collaborator side. The collaborator server provides basic CRUD (Create, Read, Update and Delete) operations along with RESTful API to communicate with. All group related information is stored in secured databases which can be downloaded only by group members. Members joining the group can be scrutinized by any mechanism the group owners decide, e.g., by checking registration (membership) numbers or by incorporating regulators that check government issued certificates. Once a group of desired members is formed, it can be disconnected from the starting coordination point without disruption and can optionally start its own coordinating server by reusing the collaborators resources. Hence, groups are formed and spin off as root leaves from coordinating servers and then later disconnect from it to run their own coordinator in the process.

B. Services required to run collaboration application

The main resource information shared at the collaborator for a group includes (but is not limited to) information for overlay network, private addresses for distributed database, shared network drive (GlusterFS), blockchain channels, and data for genesis (blockchain) channel. The blockchain infrastructure starts up using Hyperledger Fabric containers (version 2.5) using custom scripts. Main components of the blockchain structure includes a 'peer' (as shown in Fig. 2) which saves data related events on a blockchain channel against a program (chaincode or smart contract) installed on it. Other blockchain resources running as containers in each organization include ‘orderer’ which manages order of transactions on blockchain channels, Certificate Authority (CA) to securely register or unregister users with credentials such as TLS (Transport Layer Security) certificates. Membership Service Provider (MSP) runs along side CA tocoordinate registrations including the membership for other servers and CA itself.

Each organization also spins up an IPFS (Inter-Planetary File System) container and configures it privately with IPFS containers running on other organizations that are part of the group. Only data that needs to be regulated among groups is stored on IPFS and its CID (Content Identifier), which is the hash of data is shared with others over the collaboration blockchain channel. To avoid data explosion and minimize blockchain transactions, a lightweight custom chaincode is installed on all blockchain channels that allows storing and retrieving strings such as the CID for different organizational structures, e.g., for a group of breeders and processors. For data that is not stored on blockchain, a Time Stamping Authority (TSA) application running on a legitimate group node is used to track the changes for files. In the beef supply chain application, once animals move across organizations, their private or public data is disclosed using CIDs for data retrieval by organization that owns the animal at any instant.

C. Internet of things as the enabler for emissions tracking

Organizations in a group retrieve and start IoT application locally to allow consuming data from various processes in their domain. The application, distributed as packaged containers uses open source Mainflux software to start sensors and channel interfaces to consume, store and share data using Internet Protocol (IP) addresses. For the beef chain application, we focus on the sensors (energy, feed, by-products, packaging, plantation, fertilizers, pesticides, processes, cleaners and machinery) as shown in Table 1. Table 1 summarizes factors used in our example to calculate emissions against the amount of resources consumed by organizations. The factors are maintained and retrieved from an ‘emissions server’ by mutual agreement (voting). An NGO, a regulator or any of the participating organization can serve as ‘emission server’. For each sensor, several channels are turned on to consume categorical data, e.g., for byproducts sensor, the channels includes interface for methane, manure and waste data. Each group coordinates through collaboration blockchain channels to vote for the emissions calculation factor to use. This facilitates making groups that cater to geographical groups, e.g., a local Michigan group. Emission factors are coordinated and maintained using a flask-based RESTful service supporting CRUD operations that either runs on a voted group member’s node or at a new coordinated domain similar to a collaborator node. To allow sensors to consume all types of data traffic, a number of messaging formats including HTTP (Hypertext Transfer Protocol), MQTT (Message Queuing Telemetry Transport), CoAP (Constrained Application Protocol), OPC-UA (OPC Unified Architecture), and LoRa wireless interface are configured and connected to the database suitable for storing data (as shown in Fig. 3).

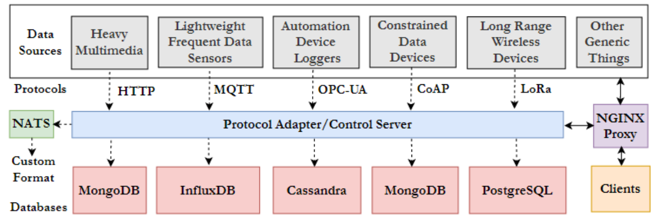
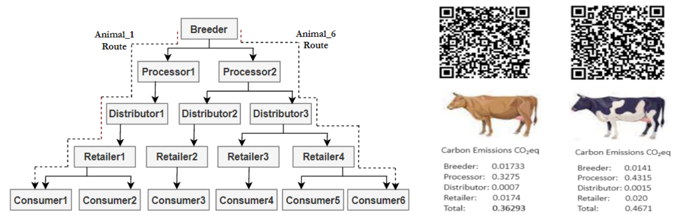


Fig. 3: Emissions IoT sensor application allow consuming different data traffic types to store it in pre-configured databases.



(a) Routes of animals (b) Emissions of animals

Fig. 4: Traceability data for $animal\_1$ (a_1) and $animal\_6$ (a_6) taking different (a) network routes, and (b) emissions reported by QR code with a_1 on left and a_6 on right side.

D. The carbon footprint tracking system

The carbon footprint tracking application works by setting up local IoT and sensor container services to record and track resource consumption of different categories in each organization. We keep in view realistic scenario of 10 animals growing at breeder for 15 months and moving through chain when reporting proportion of resource consumption (as shown in Table II). Organizations mutually setup private IPFS database nodes to store traceability records of emissions calculated from each organization when animals leave. Emissions are calculated from factors maintained and pulled by emissions server running as an independent organization with CRUD and RESTful exposed services to which all group members connect. Emission factors are pulled from literature, NGO (Non Government Organization) or government backed reporting sites and vetted (using voting) before being finalized for used. This flexibility enables creation of local or global emissions ‘zones’ with their own specific emission ranges. At the end, consumers can also optionally report distance travelled to buy packaged beef and method of cooking in attempt to get final last mile emissions. Customers are also able to see per pound (lb) or per animal emissions stored at consumer blockchain node that serves multiple clients. Finally, to harden security and privacy, along with implementing standard secure software development practice, accessing container services requires user credentials to be passed or accessed in the form of login passwords, security certificates, API tokens and encryption keys. Hence, a secure multi-function peer-to-peer collaboration group is setup with organizations mutually controlling their part of the shared data without any concerns of compromise.

IV. Results and Discussion

For testing, a beef supply chain specific scenario is set up including a breeder, 2 processors, 3 distributors, 4 retailers, 6 consumers and 1 emissions regulation server for maintaining

TABLE I: Sources from regulatory platforms and literature used in calculating CO_2eq emissions.

Category	Emission Source	CO_2 Emissions Mentioned/Derived from Literature and Online Source	Ref	Impact Factor
Energy	Electricity	4.33×10^{-4} metric tons CO_2/kWh	[27]	Moderate
	Diesel	10.180×10^{-3} metric ton CO_2/gallon	[27]	High
	Fossil	9.04x10^{-4} metric tons CO_2/pound	[27]	Very High
	Gasoline	8.887×10^{-3} metric tons CO_2/gallon	[27]	High
	Natural Gas	0.0053 metric tons CO_2/therm	[27]	Moderate
	Steam	8.119×10^{-6} metric tons CO_2/gallon	[28]	Moderate
	Solar	Offsets 50 grams of CO_2/kWh	[29]	Negative
	Wind Turbine	Offsets 6 grams of CO_2/kWh	[30]	Negative
Feed	Alfalfa Hay	1 kg corresponds to 0.07 kg CO_2eq	[31]	Low
	Distiller's Grain	1 kg corresponds to 859 g CO_2eq	[32]	Moderate
	Corn/Maize	1 kg corresponds to 0.14 kg CO_2eq	[31]	Low
	Milk Replacer	1 kg corresponds to 620 g CO_2eq	[33]	Low
	Soybean	1 kg corresponds to 0.32 kg CO_2eq	[31]	Low
	Vitamin/Mineral Mix	1 kg corresponds to 500 g CO_2eq	[31]	Low
	Protein/Fat Mix	1 kg corresponds to 750 g CO_2eq	[33]	Moderate
	Grass Hay	1 kg corresponds to 0.15 kg CO_2eq	[31]	Low
	Byproduct Waste	1 kg corresponds to 500 g CO_2eq	[33]	Low
	Seeds	1 kg corresponds to 1.2 kg CO_2eq	[34]	Moderate
	Barley	1 kg corresponds to 570 g CO_2eq	[35]	Low
	Oats	1 kg corresponds to 570 g CO_2eq	[35]	Low
	Wheat	1 kg corresponds to 590 g CO_2eq	[35]	Low
	Rye	1 kg corresponds to 870 g CO_2eq	[35]	Moderate
	Others	1 kg corresponds to 500 g CO_2eq	[33]	Low
Byproducts	Methane	220 pounds methane per cow/year 5500 pounds of CO_2eq per cow/year	[36]	High
	Manure	30000 g CO_2eq per tonne of storage	[37]	High
	Waste Discharge	1 kg corresponds to 500 g CO_2eq	[33]	Moderate
		1.82 metric ton CO_2eq per gallon	[38]	Very High
	Blood Disposal	216 mL methane per g of volatile substance; 1.82 metric ton CO_2eq per gallon	[38]	Very High
Packaging	Plastic	1.7 kg CO_2 per kg of plastic	[39]	High
	Paper	942 kg CO_2eq per metric ton paper	[40]	High
	Cardboard	0.94 kg CO_2eq per kg of material	[41]	High
Plantation	Trees	0.060 metric tons CO_2eq/urban tree	[27]	Negative
	Seeding	1.17 kg CO_2eq/kg seeds sowed	[42]	High
	Liming	0.59 kg CO_2 per kg lime application	[43]	Moderate
Fertilizers	Nitrogen	2.52 kg CO_2/kg of ammonium nitrate	[44]	Very High
	Potash	0.23 kg CO_2/kg potash muriate	[44]	Low
	Phosphate	0.73 kg CO_2/kg of phosphate	[44]	Low
	Others	0.5 kg CO_2/kg of product application	[44]	Low
Pesticides	Fungicide	3.9 kg CO_2/kg of mixed fungicide	[45]	Very High
	Herbicide	3 kg of CO_2/kg of mixed herbicide	[45]	Very High
	Insecticide	3.7 kg of CO_2/kg of mixed insecticide	[45]	Very High
Processes	Heating	0.19 kg CO_2eq/kWh of HVAC process	[46]	Moderate
	Cooling	0.19 kg CO_2eq/kWh of HVAC process	[46]	Moderate
	Electro-chemical	0.25 kg CO_2eq per kWh	[47]	Low
	Others	0.19 kg CO_2eq/kWh of process	[46]	Low
Cleaners	Cattle-Cleaner	0.46 kg CO_2eq per kg of product	[48]	High
		5.16 kg CO_2eq per kg of product	[48]	Very High
	Facility-Cleaner	0.7 lb CO_2eq/ per lb cleaning agent	[49]	Very High
	Groundwater	0.22 g CO_2 per L of ground water	[50]	Low
	Brackish Groundwater	0.35 g CO_2 per L of brackish water	[50]	Low
	Desalinated Groundwater	1.52 g CO_2 per L of desalinated water	[50]	Low
	Recycled Water	0.12 g CO_2 per L of recycled water	[50]	Low
Machinery	Pumps	4.33×10^{-4} metric tons CO_2/kWh	[27]	Moderate
	Fans	4.33×10^{-4} metric tons CO_2/kWh	[27]	Moderate
	Site Transport	10.180×10^{-3} metric ton CO_2/gallon	[27]	High
	Materials Processing	4.33×10^{-4} metric tons CO_2/kWh	[27]	Moderate
	Materials Handling	4.33×10^{-4} metric tons CO_2/kWh	[27]	Moderate
	Compressed Air	4.33×10^{-4} metric tons CO_2/kWh	[27]	Moderate
	Electronics	4.33×10^{-4} metric tons CO_2/kWh	[27]	Moderate
	Others	Offsets 50 grams of CO_2/kWh	[29]	Negative
Consumption	Roast/Bake	6.97 kg CO_2e per kg of product	[51]	High
	Toast/Broil/Grill	4.91 kg CO_2e per kg of product	[51]	High
	Slow Cooker	0.77 kg CO_2e per kg of product	[51]	Low
	Deep Fry	3.25 kg CO_2e per kg of product	[51]	High
	Steam	3.28 kg CO_2e per kg of product	[51]	High
	Boil	4.23 kg CO_2e per kg of product	[51]	High

emissions factors. Except for consumers, all organizations start local IPFS, blockchain nodes, databases and IoT sensors. For consumer, only one instance of IPFS, and blockchain node is run at a dedicated location serving all consumers with a RESTful flask application to record their feedback and retrieve cattle's public available emissions traceability data using a QR code. The whole setup is run over multiple IP reachable Virtual Machines (VMs) using Linux (Ubuntu 22.04) with a minimum RAM of 8GB and 40GB Hard Disk. The setup can be run on a cloud as well as on local machine. Each organization controls their own local setup of containerized applications comprising blockchain nodes, distributed database nodes, local IoT resources exposing sensors and channels along with a number of local databases to store emissions contributing data.

Emissions are calculated by tracking movement of 10 animals from end-to-end using data of 11 beef supply chain specific emissions categories (as shown in Table II). Table II shows amount of resources consumed with different units (under 'Unit' column) as animals move from 1 Breeder ($B1$) to 2 Processors($P1$,$P2$) and reach 6 consumers ($C1$-$C6$) through 3 Distributors ($D1$-$D3$) and 4 Retailers ($R1$-$R4$). Last 5 rows of Table II show total emissions accumulated from left to right along with the days that have gone by as animals are in transit. We also track in detail two specific animals moving on different routes as shown in (Fig. 4a). The resource consumption data is synthesized keeping in view realistic cattle growth stages, using realistic parameters from sources like USDA, FAO and other beef chain production related agencies.

First through the collaborator, the required infrastructure of organizations is established along with necessary blockchain channels and privately connected IPFS network. Sensors and channels are set up for only the type of traffic that is expected in each organization, e.g. retailer organizations only need to capture electricity, wasted meat, packaging material, refrigeration and other processes such as machinery used for cutting meat. For carbon emissions calculation, final aggregated values are used locally or sent to a federated regulatory authority using secure blockchain. An example of shared data is the final value of total feed consumed for 15 months at breeder facility. The framework makes it possible to calculate emissions at any instant (e.g. 1 minute of electricity use) by taking sensor records and retrieving total emissions against it from emissions server. The regulatory authority maintains a federated record of emission factors from vetted online resources (e.g. research articles). Vetting is done over blockchain 'emissions-channel' with support of an NGO overlooking local environment. By storing underlying details against each emission factor, the emissions server allows flexibility to experiment with the underlying factors, e.g. changing boiler efficiency rate to get a new heating emissions factor. Use of blockchain channels allows a secure and reliable way to maintain emissions for cross checking by regulators as animals transit.

We use an example of 10 animals on a farm to illustrate emissions generated over time, tracking their physical characteristics, resource consumption, and carbon emissions, particularly for two animals ($animal\_1$) and ($animal\_6$) using sensors. Final aggregated values over 18 months at breeder, shown in Table 2, highlight emissions per lb of meat at 0.051 metric tons of CO_2eq. Key characteristics like $weight$, $color$, and age are also documented. For the 10 animals (in order), the weight in kilograms {660, 663, 666, 669, 772, 775, 778, 882, 885, 888} and age in days {450, 480, 510, 540, 570, 600, 630, 660, 690, 720} is recorded at the end of 548 days leaving breeder. We consider a breeding ranch with a total are of 100 hectare (ha) with a planted area of 50 ha.

In our example, half of the animals go to a smaller processor handling 40 animals daily (20 small, 20 large), processing 13,400 lbs of meat, and packaging 9,380 lbs. The other half go to a larger unit handling 100 animals daily, yielding 22,900 lbs of meat and packaging 16,030 lbs. Over 3 days, the emissions per lb of meat are 0.3275 metric tons of CO_2eq for $P1$ and 0.4315 metric tons of CO_2eq for $P2$. Meat packages from 2

TABLE II: Resources consumed in the meat supply chain against animals movement and resultant CO_2eq emissions.

Emission Source	**Unit**	**Breeder**	**Processor**		**Distributor**			**Retailer**				**Consumer**					
		B1	P1	P2	D1	D2	D3	R1	R2	R3	R4	C1	C2	C3	C4	C5	C6
Electricity	kWh	50000	500	1000	0	0	0	100	200	350	400	0.1	0.3	0.5	1	1.2	1.5
Diesel	lb	5000	50	80	0	0	0	0	0	0	0	0	0	0	0	0	0
Fossil	lb	4000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gasoline	lb	4500	30	50	3500	6000	10000	0	0	0	0	0	0	0	0	0	0
Natural Gas	$feet^3$	100000	500	1000	0	0	0	0	0	0	0	0	0	0	0	0	0
Steam	lb	200000	1000	2000	0	0	0	0	0	0	0	0	0	0	0	0	0
Bio Gas	$feet^3$	0	0	5000	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar	kWh	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0
Alfalfa Hay	lb	30000	500	1000	0	0	0	0	0	0	0	0	0	0	0	0	0
Distiller's Grain	lb	20000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corn/Maize	lb	30000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Milk Replacer	lb	20000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soybean	lb	5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vitamin/Mineral Mix	lb	10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Protein/Fat Mix	lb	20000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grass Hay	lb	30000	500	1000	0	0	0	0	0	0	0	0	0	0	0	0	0
Byproduct Waste	lb	10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Seeds	lb	10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Barley	lb	30000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oats	lb	20000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wheat	lb	10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rye	lb	10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	lb	5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Methane	lb	3000	2000	5000	0	0	0	0	0	0	0	0	0	0	0	0	0
Manure	lb	200000	3000	10000	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste Discharge	lb	0	20000	45000	0	0	0	30	40	60	80	0	0	0	0	0	0
Blood Disposal	gal	0	200	500	0	0	0	0	0	0	0	0	0	0	0	0	0
Plastic	kg	50	50	150	5	6	6	30	35	40	45	0	0	0	0	0	0
Paper	kg	0	30	80	5	5	7	30	35	40	45	0	0	0	0	0	0
Cardboard	kg	0	50	150	10	12	11	20	25	30	35	0	0	0	0	0	0
Trees	ha	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Seeding	lb	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Liming	lb	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nitrogen	lb	4000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Potash	lb	2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phosphate	lb	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	lb	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fungicide	lb	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Herbicide	lb	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Insecticide	lb	120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heating	kWh	30000	50	100	0	0	0	0	0	0	0	0	0	0	0	0	0
Cooling	kWh	40000	100	250	400	700	1200	100	200	350	400	0.1	0.3	0.5	1	1.2	1.5
Electro-chemical	kWh	10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	kWh	10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cattle-Cleaner	lb	500000	3000	7000	0	0	0	0	0	0	0	0	0	0	0	0	0
Facility-Cleaner	lb	100000	2000	5000	0	0	0	0	0	0	0	0	0	0	0	0	0
Groundwater	Gal	500000	10000	0	0	0	0	5	10	20	30	0	0	0	0	0	0
Brackish Groundwater	Gal	0	0	20000	0	0	0	0	0	0	0	0	0	0	0	0	0
Desalinated	Gal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recycled Water	Gal	0	12000	30000	0	0	0	0	0	0	0	0	0	0	0	0	0
Pumps	kWh	10000	10	30	0	0	0	10	10	10	10	0	0	0	0	0	0
Fans	kWh	5000	10	30	0	0	0	10	10	10	10	0	0	0	0	0	0
Site Transport	lb	5000	10	25	0	0	0	10	10	10	10	0	0	0	0	0	0
Materials Processing	kWh	20000	20	40	0	0	0	20	20	20	20	0	0	0	0	0	0
Materials Handling	kWh	15000	20	40	0	0	0	20	20	20	20	0	0	0	0	0	0
Compressed Air	kWh	15000	5	15	0	0	0	5	5	5	5	0	0	0	0	0	0
Electronics	kWh	3000	5	15	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	kWh	10000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roast/Bake	lb	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Toast/Broil/Grill	lb	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Slow Cooker	lb	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0
Deep Fry	lb	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
Steam	lb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0
Boil	lb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
Transport	lb	0	500	1500	3500	6000	10000	0	0	0	0	10	20	30	40	50	60
Distance	mile	0	150	300	1200	2100	2900	0	0	0	0	10	20	30	40	50	60
Total Emissions From Organization (CO_2eq)	metric tons	356.109	4389.55	9882.69	3.824	6.545	10.89	10.47	15.39	24.12	28.54	0.170	0.30	0.34	0.54	0.688	0.084
Total Emissions Per lb of Meat (CO_2eq)	metric tons	0.051	0.3275	0.4315	0.0007	0.001	0.0015	0.0174	0.019	0.02	0.02	0.0085	0.0076	0.0057	0.0068	0.0068	0.0083
Accumulated Emission Per lb of Meat (CO_2eq)	metric tons	0.051	0.3756	.4825	0.3763	0.4835	0.484	0.3930	0.5015	0.3963	0.3963	0.4015	0.4006	0.5082	0.4031	0.4031	0.4046
Total Distance Traveled from Origin	mile	0	150	300	1350	2400	3200	1350	2400	3200	3200	1360	1370	2430	3240	3250	3260
Total Days Passed from Origin	days	548	552	553	556	558	600	561	573	620	625	566	567	579	627	633	634

processing (abattoir) plants are moved by 3 distributors, each traveling varying distances that results in different emissions from fuel and storage. Detailed resource consumption is shown in Table 2, with $D1$ delivering to $R1$, $D2$ to $R2$, and $D3$ to $R3$ and $R4$. The final emissions per lb of meat are 0.0007 metric tons of CO_2eq for $D1$, 0.001 metric tons for $D2$, and 0.0015 metric tons for $D3$. The final value at $P1$ comes out to be 0.3275 metric tons of CO_2eq and 0.4315 metric tons of CO_2eq from $P2$. Retailer, the final step in the meat supply chain, uses resources for functions like processing, cold storage, and refrigeration. For our example, emissions per lb of meat are 0.0174 metric tons CO_2eq for $R1$ after 5 days, 0.019 metric tons for $R2$ after 6 days, 0.02 metric tons for $R3$ after 7 days, and 0.02 metric tons for $R4$ after 9 days, as detailed in Table II. Consumers contribution to emissions comes through travel and cooking. In our example, 6 consumers, each using a different cooking method and traveling varying distances to retail stores, contribute to final emissions by adding 401, 400, 508, 403, 403, and 404kg of CO_2eq per lb of meat.

A summary of proportion of emissions generated throughout different stages of the beef chain as 10 animals move from end-to-end is given in Fig. 5 (a-f). Fig 5(a), Fig(b) and Fig(c) shows contribution of emissions from different categories for the 10 animals as they move across breeder and 2 processors

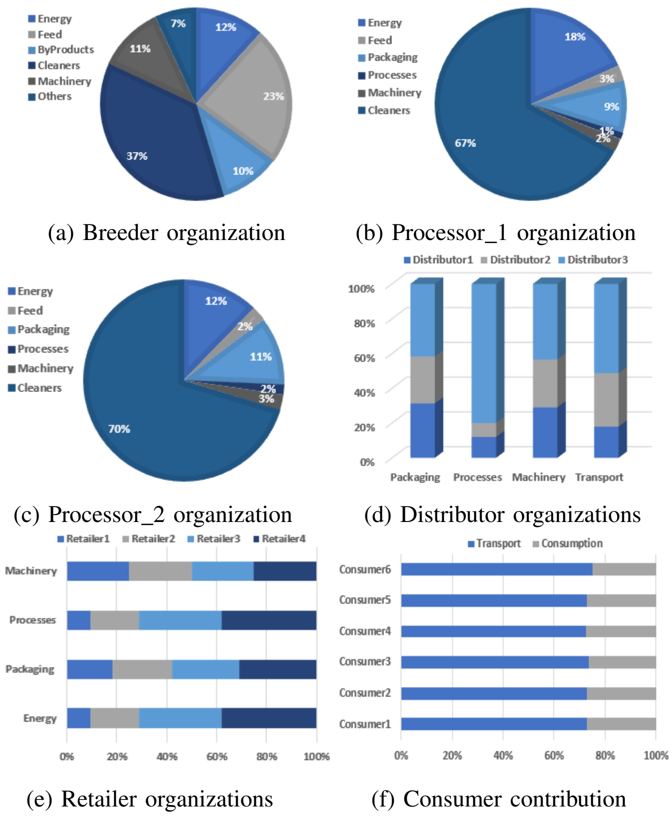


Fig. 5: Proportion of metric tons of CO_2eq emissions contribution at different stages of beef chain.

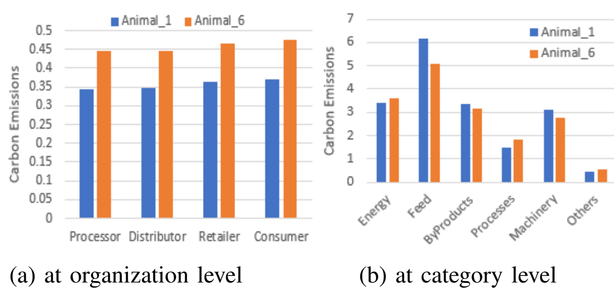


Fig. 6: Emissions contribution in metric tons of CO_2eq (y-axis) for $animal\_1$ and $animal\_6$ at different domains.

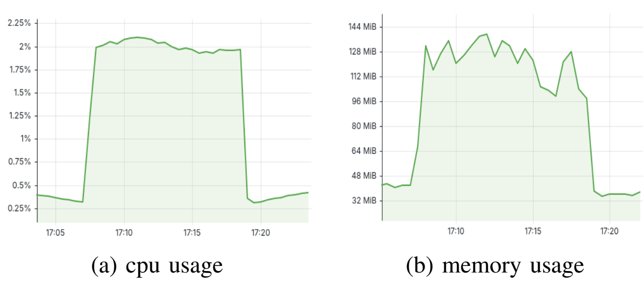


Fig. 7: Resource consumption for IoT application (a) y-axis shows percent of CPU use with timeline on x-axis (b) y-axis shows memory use in MiB with timeline on x-axis. Application is setup for organizations operating in Michigan using EDT time (UTC-4:00 hrs) on x-axis.

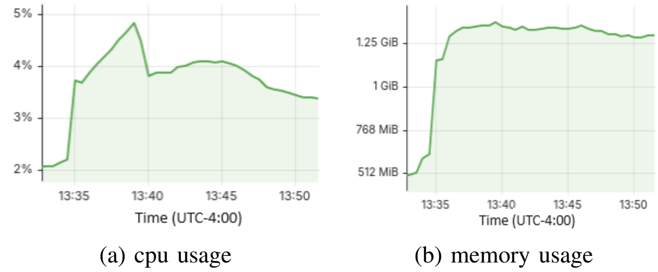


Fig. 8: Resource consumption for IoT application with service provisioning for blockchain and IPFS (a) y-axis shows percent of CPU use (b) y-axis shows memory use in MiB.

(5 animals each). Fig 5(d) and Fig 5(e) shows percentage of emissions taken by top categories as processed animals move through 4 distributors to 4 retailers. Fig 5(f) shows last mile emission contribution from consumers as they travel and cook beef. Figure 6 gives a consolidated view of individual animals contribution for the chain. Fig 6(a) is a combined summary of the two precisely tracked animals contributing at organization level and Fig 6(b) is is their total contribution in metric tons of CO_2eq for different categories. The reported statistics in Fig 6(a-b) are embedded in QR code for consumers to decode as shown in Fig. 4(b). Detailed resource consumption is reported by tracking two animals starting from same breeder. Emissions for $animal\_1$ are 0.0173 per lb of CO_2eq at the breeder and 0.37143 per lb overall, while $animal\_6$ has 0.0141 per lb at the breeder and 0.4754 per lb overall. At the end, accumulated emissions for $animal\_1$ comes out to be 0.37143 per lb of CO_2eq and 0.4754 per lb of CO_2eq for $animal\_6$.

System load from IoT application is tested by continuously sending sensor data over 10 channels for 10 minutes with each packet is 1kb in size and storing it in MongoDB. Around 15 IoT services run for IoT application to provide functions such as authentication, databases, routing and message queuing. The IoT services combined CPU usage averages around 2% (Fig. 7(a)) and combined maximum memory usage goes to 130MiB peak (Fig. 7(b)). Aggregated network transmission rate for the IoT application averaged at 60kbps thereby providing lightweight functionality to accommodate other functions. Local IoT nodes and services were also tested for breeder to see the applications suitability to be run in combination with blockchain and IPFS. IoT related containers (with 15 sub-services) start (with immediately serving blockchain and IPFS nodes) with a load of 512MiB and CPU utilization of 2% with increase to 1.25GiB and 4% as all services coordinate together to maintain sensor data (as shown in Fig. 8). Finally, by leveraging provided containers, the system's resource usage can be effectively managed and fine-tuned, allowing for flexible adjustments to hardware limitations by capping data capturing and processing demands as needed.

V. Conclusion

Complex supply chains such as the 'beef chain' significantly impacts the environment through emissions. Tracking carbon footprint is challenging due to the lack of vertical integration across supply chain stages. To address this, we propose a decentralized blockchain-based framework integrated with IoTs and distributed databases to capture detailed emissions data throughout the supply chain. This framework supports precise carbon emission tracking, ensures transparency, and integrates diverse information sources without privacy concerns. Using a distributed blockchain and IoT infrastructure, it enables secure data capturing and policy communication, facilitating reliable traceability and scalable environmental data sharing. Ultimately, this solution aims to promote emissions reduction and management across complex supply chains.

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