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RESEARCH REPORT

Leveraging Circular Bioeconomy for Resilience in Sudan's Refugee-Hosting Communities

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Acronyms

BSF	Black Soldier Fly
CBE	Circular Bioeconomy
CE	Circular Economy
CSE	Circular Sanitation Economy
FAO	Food and Agriculture Organization of the United Nations
HDP	Humanitarian–Development–Peace
IDP	Internally Displaced Person
MENRPD	Ministry of Environment, Natural Resources and Physical Development
MSW	Municipal Solid Waste
NDC	Nationally Determined Contribution
NGO	Non-Governmental Organization
RRR	Resource Recovery and Reuse
WASH	Water, Sanitation and Hygiene

Summary

Sudan's overlapping crises of conflict, displacement, climate stress, and service collapse have pushed millions of people into extreme vulnerability, placing unprecedented pressure on food, water, energy, and sanitation systems in refugee-hosting regions. This paper explores how circular bioeconomy approaches can transform these pressures into opportunities for resilience in three highly affected states: White Nile, Gedaref, and Kassala. Drawing on a desk-based assessment and evidence from comparable humanitarian contexts, the study identifies practical, low-infrastructure pathways that convert locally available organic waste and by-products into food, energy, soil inputs, and livelihoods.

The analysis highlights five priority entry points: nutrient recycling for food system resilience; decentralized bioenergy for clean cooking and basic services; feed production for displaced livestock; small-scale wastewater reuse and greywater irrigation; and community-based bioproduct enterprises. Together, these pathways demonstrate how waste streams can be reframed as assets that strengthen self-reliance, reduce environmental degradation, and ease pressure on overstretched humanitarian systems.

Embedding CBE within the humanitarian–development–peace nexus, the paper shows how circular solutions can position displacement settings not only as sites of need, but as spaces for innovation, regeneration, and recovery that simultaneously meet immediate needs and build longer-term adaptive capacity. It provides actionable guidance for humanitarian and development actors seeking scalable, context-sensitive interventions that deliver co-benefits for the environment, society, and the economy.

Future work will prioritize field-based assessments, co-design with displaced and host communities, and partnerships with humanitarian actors to ground-truth waste flows, assess health safeguards, and develop state-specific implementation models that can be piloted and scaled under real operational conditions.

1. Introduction

1.1. Context and rationale

Sudan is currently facing an overlapping crisis of violent conflict, mass displacement, and deepening food insecurity. Recent analyses describe the situation in Sudan as one of the world's most severe food crises, with conflict, macroeconomic collapse and disrupted markets eroding people's ability to access sufficient food and basic services (IPC, 2023). The scale and severity of food insecurity are stark: the 2023 IPC Acute Food Insecurity analysis estimates that around 20.3 million people are facing high levels of acute food insecurity (IPC Phase 3 or above), including 6.3 million in emergency (IPC Phase 4). This means that nearly half of Sudan's total population is experiencing severe food insecurity, underscoring the unprecedented scale of humanitarian need.

Sudan's acute food insecurity is also deeply rooted in wider security, climate and environmental pressures. The Global Peace Index (2023) ranks the country among the least peaceful nations worldwide, with very low scores for violent crime, internal displacement, political terror, and instability (IEP, 2023). These conditions weaken institutional capacity and place an extraordinary strain on host communities, where water supply, sanitation, waste management, and access to clean energy are already limited and often unreliable (MENRPD & UNEP, 2020). The country also relies heavily on pastoral, agropastoral, and rainfed agricultural systems, all of which employ most of the population and are highly dependent on predictable rainfall, fertile soils, and access to natural resources. This resource base is under increasing pressure: rainfall variability, land degradation, advancing desertification, and recurrent droughts have steadily reduced agricultural productivity and the capacity of rural households to cope with shocks, thereby intensifying the food security crisis.

Evidence from conflict-affected regions shows how climate change and insecurity intersect to shrink cultivated land, depress yields, disrupt agricultural activities and markets, and drive up food prices, with scales varying by region. At the same time, widespread displacement and unsustainable resource use are intensifying pressure on already fragile water, food and energy systems. Natural resource–based pressures have intensified intercommunal conflict and created complex challenges for managing resources already strained by climate change. These dynamics are pushing the region toward ecological and social tipping points, as climate change, weak natural resource management, and conflict reinforce a self-perpetuating cycle of instability (UNEP, 2025). Together, these stresses undermine the ability of both internally displaced persons (IDPs) and host communities to meet their basic needs, sustain their livelihoods, and build resilience. In this context, there is a growing need for approaches that promote social cohesion and peacebuilding while reinforcing humanitarian response, expanding essential services, improving resource efficiency, and restoring livelihoods.

The circular bioeconomy (CBE) offers a practical and transformative pathway to leverage locally available organic materials, biomass, and other waste streams to boost resilience in crisis-affected areas. Evidence from refugee-hosting regions in East Africa indicates that CBE approaches, such as nutrient recycling and grey water reuse, can boost resilience, reduce pressure on degraded ecosystems, and create livelihood opportunities for both refugees and host communities (Adam-Bradford et al., 2022; Gebrezgabher et al., 2025). Framing CBE within the humanitarian–development–peace nexus is particularly important in Sudan, where overlapping crises require solutions that address immediate humanitarian needs while strengthening long-term stability. CBE approaches offer a unique bridge across this nexus by improving essential services, supporting livelihoods, and reducing resource-based tensions in displacement-affected areas.

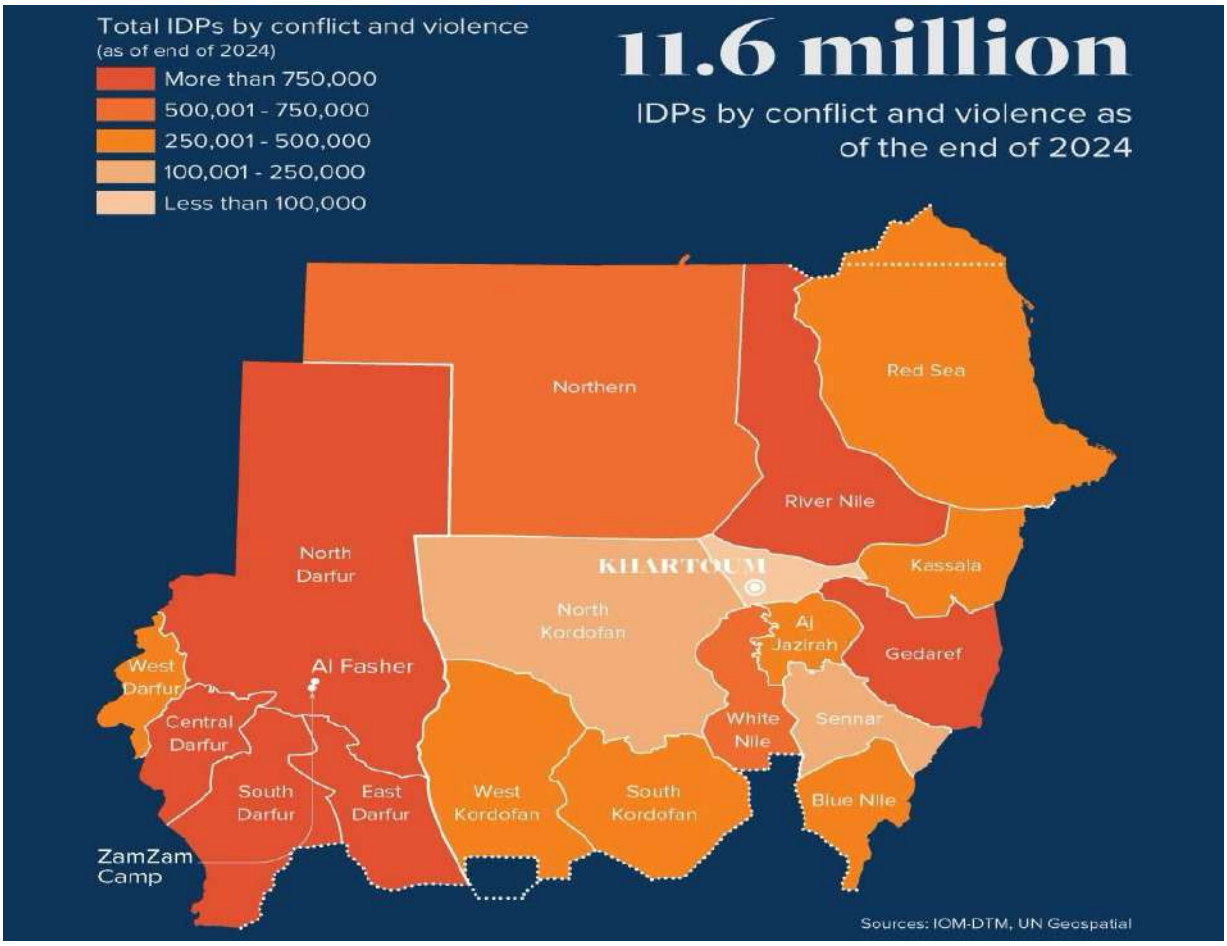

Figure 1: *Distribution of internally displaced persons (IDPs) across Sudan by conflict and violence (end of 2024). Image Source: IOM-DTM; UN Geospatial (2024).*

1.2. Report aim and objectives

The report is structured to inform strategic decision-making by UNHCR, government partners and humanitarian and development actors active in these locations. Specifically, it provides a basis for identifying practical CBE entry points that align with existing programs and strategies to strengthen resilience, expand sustainable livelihoods for displaced people and host communities and promote social cohesion across Sudan's crisis-affected regions. The assessment focuses on White Nile, Gedaref and Kassala (Figure 1), where large refugee and IDP populations, overstretched services and recurrent climate and market disruptions create an urgent need for resource-efficient, locally grounded interventions.

Given current limitations in data availability, restricted field access, and broader operational constraints in Sudan, this analysis is an initial desk-based assessment. On-ground verification of waste volumes, flow dynamics, or existing CBE practices was not feasible at this stage. As a result, this assessment draws on regional evidence, comparable secondary data and established CBE applications in similar agro-ecological and humanitarian contexts to identify feasible pathways relevant to White Nile, Gedaref, and Kassala. The report structure begins with an overview of Sudan's waste and resource management landscape, followed by detailed state profiles that frame the conditions shaping CBE opportunities. It then identifies priority CBE pathways and specific entry points. The report concludes with practical guidance on implementation, presenting actionable recommendations, particularly those that can reinforce food, energy and livelihood systems without requiring large or complex infrastructure.

2. Circular Economy and Waste Management

Circular economy (CE) approaches focus on closing resource loops by turning organic waste and biological by-products into inputs for agriculture, energy, materials, and livelihoods. Beyond recycling, the bioeconomy emphasizes regenerative systems where biological resources are used efficiently, circulate through multiple applications, and ultimately return to the environment in ways that sustain ecological processes. This requires a clear understanding of how biomass flows through society: how resources become waste, how they are handled, and how ecosystems that supply them are maintained. In the context of fragile and conflict-affected settings, where resources are scarce, and land is often degraded, CE approaches have significant potential to strengthen the resilience of IDPs and host communities by recovering and productively reusing water, nutrients, organic matter, and energy from locally available domestic and agricultural waste streams.

A core dimension of the CE lies in creating and capturing value from materials that would otherwise be treated as waste, and in maximizing this value to support sustainable development through improved waste management and resource recovery and reuse (RRR), including energy, water, and nutrients. CE approaches also offer important opportunities to stimulate livelihoods by generating additional income streams while enhancing nutrition diversity for IDPs and host communities, for example, through the safe reuse of greywater for home gardening. Circular economy solutions such as urban agriculture supported by greywater reuse and nutrient recovery for kitchen gardens have been widely identified as viable pathways to reduce dependence on food aid and support a transition toward greater self-reliance among refugee communities (Adam-Bradford & van Veenhuizen, 2015). The following section presents Sudan's waste and resource management landscape to identify where circular opportunities exist, where systemic constraints limit recovery and where targeted support is needed to enable feasible CBE interventions.

2.1. National Waste Context

Sudan is one of Africa's largest countries (approximately 1.9 million km²) with about 40 – 42 million inhabitants, experiencing rapid population growth and urbanization. Urban centers are expanding through largely uncontrolled sprawl, which has outpaced already strained service systems, including solid waste and wastewater management. Sudan generates an estimated 21,000 tonnes of Municipal Solid Waste (MSW) per day (about 0.5 kg per person), totaling around 7.7 million tonnes (MT) annually. Only one-third of this waste is collected, leaving more than 5 MT uncollected annually (MENRPD & UNEP, 2020). Much of this discarded waste accumulates in residential areas, open spaces and drains, where it is frequently dumped or burned. These practices block stormwater systems, increase the risk of vector-borne diseases, and contribute to local air pollution (Farouk et al., 2022). The impacts are most severe in rapidly growing towns and displacement-affected areas, where youth unemployment, informal livelihoods and overstretched municipal budgets limit the ability of communities to manage waste safely.

Sudan's capacity to manage solid waste was already weak prior to the conflict, and the ongoing war has exacerbated these challenges. A study by the Conflict and Environment Observatory (CEOBS, 2025) on the environmental costs of the war in Sudan highlights how widespread infrastructure damage, collapsing sanitation systems, and hazardous industrial leaks have intensified pollution and heightened public health risks. These environmental pressures, combined with competition over scarce resources, contribute to broader instability. At the same time, Sudan's large-scale displacement crisis, driven by conflict and climate

shocks, has significantly increased waste generation, overwhelming limited waste management infrastructure and creating acute health risks in displacement camps and urban areas. Within this context, strengthened waste management and circular bioeconomy approaches focused on waste reduction, resource recovery, and local reuse offer opportunities to mitigate environmental and health risks while supporting resilience and livelihoods. In response, organizations such as IOM and WasteAid, in collaboration with UNICEF and WHO, are supporting the delivery of Water, Sanitation, and Hygiene (WASH) services, including waste collection and hygiene promotion.

The institutional environment governing waste management is equally strained. The country does not have a national strategic plan for MSW, and responsibilities are split across national, state and municipal levels. The Ministry of Environment, Natural Resources and Physical Development (MENRPD) provides overall oversight, but municipalities are responsible for collection and disposal. This decentralized system has led to uneven service delivery, weak coordination and limited regulatory enforcement, especially where local governments lack financial and technical capacity (MENRPD & UNEP, 2020). Although environmental impact assessments are legally required for disposal sites, enforcement is inconsistent and largely limited to Khartoum State. Existing legislation, including the Environment Protection Act (2001), the Public Health Act (2008), and various state-level environmental laws, operates independently of one another. As a result, Sudan lacks a coherent policy framework to support integrated waste planning or CBE pathways.

Studies show that about 40% of Sudan's waste stream is biodegradable (MENRPD & UNEP, 2020). Paper accounts for 27%, followed by inert materials (15%), textiles (6%), glass and ceramics (5%), plastics and rubber (4%) and metals (3%). This high proportion of organic waste offers strong potential for composting, bioenergy and other CBE applications (Awad et al., 2017; MENRPD & UNEP, 2020). However, several barriers limit recovery: waste is not segregated at the source, processing infrastructure is scarce, and recycling markets are weak. Moreover, across the country, open dumping and open burning remain the main disposal methods at both official and informal sites. Engineered landfills are rare and often poorly maintained because of equipment shortages and operational challenges. The private recycling sector is small, informal and dependent on irregular material flows. Some states, such as Khartoum and Gedaref, have introduced measures, such as plastic bag bans, but enforcement is limited. As a result, Sudan continues to lose large quantities of organic material that could be used to improve soils, generate local energy, create jobs and support youth-led circular enterprises. These national conditions create broad constraints, but they do not uniformly determine opportunities across all states. Understanding how waste is generated, accessed, and managed within each state is therefore essential for identifying feasible entry points that can enhance resilience, support livelihoods, and close resource loops in crisis-affected settings. The following subsections outline the demographic, displacement, livelihood, environmental, and service-related pressures in White Nile, Gedaref, and Kassala, providing the evidence base for prioritizing context-appropriate CBE pathways.

2.1.1. White Nile State

White Nile, Sudan's largest refugee-hosting state, accommodates an estimated 650,000 internally displaced people across more than 1,300 locations, as well as 435,400 South Sudanese refugees, as of March 2025 (UNHCR, 2025). Conflict since April 2023 has intensified population movements, bringing more than 650,000 IDPs by early 2025 across more than 1,300 locations, including Khor Ajwal camp, schools and temporary shelters (OCHA, 2023a; IOM, 2024). These displacement dynamics intersect with the state's underlying demographic pressures. White Nile has an estimated population of 3.3 million, distributed across nine localities with major concentrations in Kosti, Rabak and Al Duweim (OCHA, 2023a). The state has a strong youthful demographic profile, with nearly 950,000 children under 18, and roughly 75% of residents live in rural areas, shaping both service delivery needs and vulnerability patterns (UNICEF, 2022a). The combined effect of rapid population growth, large refugee and IDP inflows, and high rural dependency places significant strain on already fragile infrastructures. These pressures are particularly acute in the water and sanitation sector. The arrival of tens of thousands of new refugees since 2023 has put intense demand on White Nile's already fragile water systems. UNHCR reports providing clean water to roughly 500,000 people through 11 water systems and daily trucking of 140 m^3, yet the per capita supply has fallen to 13 L/person/day, below the Sphere water standards of 15 L/Person/day (UNHCR, 2025a). Sanitation coverage is similarly constrained, with an average of 47 persons per latrine despite ongoing rehabilitation efforts in camps. Poor hygiene conditions heighten the risk of outbreaks, and infrastructure-related water shortages, combined with the difficulty local authorities face in adjusting systems to support large, newly arrived populations (ACAPS, 2023).

Agriculture remains the backbone of livelihood, supported by sugarcane processing and extensive cotton, livestock, and fish production (UNICEF, 2022a). However, economic decline, marked by high inflation, currency instability, and repeated market disruptions, has eroded incomes and reduced the sector's ability to sustain rural households. The weakening of agro-industrial operations, together with constrained access to inputs and unreliable markets, has left many households increasingly dependent on informal labour, remittances, or humanitarian assistance. These pressures are heightened in displacement-affected areas, where large refugee and IDP populations compete for limited employment opportunities. These livelihood challenges are compounded by the environmental burdens associated with agro-industrial activity. Studies by Ahmed et al. (2017) and Alnali et al. (2013) show that sugar-processing in Rabak and Kosti is a major source of pollution to the White Nile and its irrigation canals. This is primarily due to untreated wastewater effluent from factories carrying high loads of organic matter, nutrients and agrochemicals. Environmental stresses further compound vulnerability. The state has experienced a temperature rise of about 1°C since the 1970s, recurrent floods, erratic rainfall, drought in areas such as Al Gutaina, and groundwater decline in Al Salam and Al Jabalain (UNICEF, 2022a; OCHA, 2023a). These combined pressures highlight the need for integrated measures to curb urban and agro-industrial pollution.

2.1.2. Gedaref State

Gedaref has an estimated population of 2.3 – 2.5 million in 2023, growing at about 5% annually. Shaped by long-standing migration patterns, the state is ethnically diverse and has a notably youthful population, including 279,181 adolescents aged 14 – 19 (UNICEF, 2022b). Over one million people in local communities hosting refugees and migrants face increased stress on social services and greater vulnerability (UNICEF, 2022b). Since April 2023, Gedaref has become one of Sudan's largest reception areas for IDPs: by late 2024, it hosted 1,032,125

IDPs across 528 locations, with over 1 million arriving after the conflict began (Babekir & Aalen, 2024). Prior to this influx, the state also hosted 61,073 refugees from Ethiopia and Somalia (UNHCR, 2025). These combined population movements have placed severe strain on housing, water and sanitation systems.

Agriculture remains central to the state's economy. Gedaref accounts for 70% of Sudan's mechanized farming and supports around 7.6 million head of livestock. It is a major producer of sesame, sorghum and sunflowers (UNICEF, 2022b). However, the farming system is mostly rain-fed and highly sensitive to climate variability. Conflict has further disrupted markets and employment opportunities, resulting in widespread unemployment and inflation. Many IDPs now rely on humanitarian assistance, remittances or informal work, while host communities struggle with rising living costs and greater competition for basic resources (Babekir & Aalen, 2024). These stresses are compounded by environmental pressures. Gedaref's semi-tropical climate, with 700 – 900 mm of annual rainfall concentrated between June and September, has become more unpredictable due to climate change (UNICEF, 2022b). Floods and droughts are becoming more frequent; in 2024 alone, floods displaced more than 200,000 people nationwide and damaged key infrastructure (JRC, 2025). Soil degradation, deforestation and competition over grazing lands are worsening as population density rises and large livestock herds concentrate in the state.

Poor waste management and overstretched sanitation systems further heighten public health risks. The 2019 Gedaref WASH assessment found that only 13% of households used improved sanitation, 43% practiced open defecation, and solid waste was frequently dumped or burnt in the open, particularly outside El Gedaref town (WASH Sector Development Plan, 2019). Limited drainage and scattered dumping sites created stagnant water pools, conditions that favor mosquito breeding and increase disease transmission (Babekir & Aalen, 2024). Displacement has also increased pressure on WASH services (ACAPS, 2024). Refugee camps such as Um Rakuba rely heavily on humanitarian partners for water supply, hygiene items and sanitation infrastructure. Damage to WASH facilities along the conflict-affected eastern corridor, coupled with weak governance and limited institutional capacity, has made sustained service delivery difficult. Gender analyses consistently identify water shortages, unsafe sanitation and long queues at water points as key protection risks for women and girls, who face heightened exposure to harassment and violence when accessing basic services.

These vulnerabilities have become more acute during the ongoing conflict. Reuters reporting from August 2024 documented that Gedaref and Kassala were at the center of a renewed cholera outbreak, with 658 cases and at least 28 deaths recorded across five states since July 22, and more than 200,000 people at high risk (Siddig, 2024). In Gedaref, stagnant rainwater mixing with refuse, overflowing latrines in overcrowded displacement sites, and poor water quality were identified by local officials as major drivers of disease. Overstretched health services, limited vector control capacity and restricted humanitarian access have made containment difficult. These pressures undermine resilience and highlight the need for solutions that stabilize livelihoods, reduce environmental stress and support more sustainable resource use. Opportunities include strengthening waste recovery and composting to reduce open dumping, improving drainage and surface-water management, supporting safe water access, and developing resource-efficient local enterprises while generating income in displacement-affected communities.

2.1.3. Kassala State

Kassala, which borders Ethiopia and Eritrea, had an estimated population of 2.9 million in 2023 (OCHA, 2023b). It is Sudan's third-largest refugee-hosting state, with more than 111,069 refugees and asylum seekers as of Nov 2025 (UNHCR, 2025). Although Kassala remained relatively calm after the April 2023 conflict, it continued to receive IDPs into Halfa Al-Jadeeda and areas along the Gash River. In total, an estimated 920,700 people required humanitarian assistance in 2023. These inflows have added pressure to already stretched service systems and livelihood opportunities (OCHA, 2023b).

Agriculture, livestock, casual labor and cross-border trade form the backbone of the state economy. Kassala contributes to Sudan's agricultural "breadbasket" with about 1.7 million hectares of cultivable land (Mercy Corps, 2024). However, agricultural productivity has declined due to displacement, damaged irrigation infrastructure, shortages of inputs and rising temperatures. Wheat cultivation in Halfa Al-Jadeeda, for example, has been severely affected by a lack of fertilizers, seeds and finance (Mercy Corps, 2024; FEWSNET, 2023). Food insecurity has increased sharply, with 43% of the population projected to be in IPC Phase 3 or above between late 2023 and early 2024. Market disruptions and reduced labor availability have further constrained both production and household purchasing power.

Environmental conditions further undermine resilience. Kassala faces recurrent droughts and flash floods; the 2022 floods damaged more than 5,178 homes and disrupted farming across six localities (ACAPS, 2022). The Gash River system, essential for irrigation and domestic water supply, has suffered long-term degradation due to siltation, poor management and population pressure, making surrounding areas prone to waterlogging and soil erosion. These environmental stresses compound the challenges faced by refugees and IDPs, while also undermining already fragile host communities. It creates conditions of "double displacement" in which both newcomers and long-settled populations face layered vulnerability. According to the 2019 Kassala WASH and Waste Development Plan, poor solid waste management, including widespread open dumping and burning in urban and peri-urban areas, contributes to blocked drains and stagnant water, amplifying flood impacts and seasonal disease risks (RedR UK, 2019). Households frequently dispose of waste in open spaces and the lack of structured collection systems leads to the accumulation of refuse during the rainy season.

Despite these challenges, the water supply in refugee settlements within Kassala is said to be comparatively more stable. Seven refugee camps receive an average of 14,230 m^3 of water per day, equivalent to 21 L/person/day, meeting Sphere standards (UNHCR, 2025b). In addition to UNHCR, a few organizations, including UNICEF, IOM, and WasteAid, are actively supporting WASH interventions in Sudan. These efforts focus on improving waste management, promoting hygiene, and increasing access to safe water for displaced populations. For example, IOM has conducted waste management campaigns targeting hundreds of thousands of displaced people, while UNICEF and WasteAid support hygiene services and community-based sanitation initiatives to reduce health risks and environmental contamination. The wider state continues to face significant governance and coordination barriers, including high telecommunications costs and unstable service provision that hinder information flow and operational planning (IRC, 2025). Population movements and limited administrative capacity further stretch local WASH systems, particularly in peri-urban areas and informal settlements (UNHCR, 2025b). These systemic gaps mean that even where minimum water supply standards are met in camps, surrounding communities and displacement sites remain highly vulnerable to disease outbreaks. Weak sanitation infrastructure, poor waste-disposal practices, and fragmented service delivery directly

contribute to a deteriorating public health environment across the state. Crowded settlement patterns and inadequate waste disposal in peri-urban areas further heighten exposure to vector-borne and waterborne diseases. Reuters reporting in 2024 noted that stagnant rainwater mixed with refuse in Kassala had contributed to a rise in cholera cases during the rainy season, particularly in crowded displacement sites where sanitation is limited. Such outbreaks reflect the intersection of environmental degradation, weak waste systems and limited access to safe water. Overall, the convergence of demographic pressure, displacement, degraded ecosystems, and declining agricultural productivity in Kassala underscores the need for CBE solutions that address Kassala's mix of agricultural decline, waste accumulation, and fragile water systems. Opportunities lie in improving the management of crop residues and urban organic waste, restoring the Gash River's productive potential through soil- and water-conserving practices, and supporting micro-enterprises that can convert locally available biomass into valuable inputs.

2.2. Energy Services

Energy access reflects similar structural fragilities. Sudan's energy sector relies heavily on biomass, which provides the bulk of the total primary energy supply (Omer, 2018; Al-Rikabi et al., 2025). Although some industrial bioenergy capacity exists, such as sugarcane bagasse-based power in White Nile (104 MW from 1,350 kt/year of bagasse) and New Halfa in Kassala (6 MW from 123 kt/year), household access to reliable energy is very limited. Frequent grid failures, chronic fuel shortages, and high costs affect the domestic, social, and productive uses of electricity (MENRPD & UNEP, 2020). Most households rely on firewood and charcoal for cooking, contributing to widespread deforestation and degradation of dryland ecosystems. In parallel, diesel generators remain an important but costly backup power source for health facilities, water systems, and small enterprises, particularly in urban and peri-urban centers. Rising fuel prices and difficulties obtaining spare parts have made these systems increasingly unaffordable and unreliable (IPC, 2023; ACAPS, 2023). These constraints highlight the need for decentralized, locally sourced energy options, particularly CBE-driven solutions such as biogas, briquettes, and other residue-based fuels, which can complement limited grid supplies in White Nile, Gedaref, and Kassala (MENRPD & UNEP, 2020; Al-Rikabi et al., 2025).

2.3. Waste Management Services

White Nile, Gedaref and Kassala generate substantial quantities of organic waste from agriculture, livestock, agro-processing and urban activities (MENRPD & UNEP, 2020). Evidence shows that biomass contributes nearly 87% of Sudan's total energy supply, with agricultural residues playing a major role (Omer, 2018). Although detailed, state-level waste estimates remain limited, all three states lie within Sudan's main agricultural corridor, which produces large volumes of sorghum and millet stover, sesame husks, cotton stalks and groundnut shells (IPC, 2023; Mercy Corps, 2024). Recent studies show that the 2023/24 cereal harvests produced sizeable volumes of associated residues consistent with this pattern, much of which is currently sustaining livestock herds, including the large numbers of displaced animals now concentrated in hosting states such as Gedaref and Kassala (FAO, 2024). Urban and industrial organic wastes add to this resource base. Most municipal waste across the country is biodegradable, but is often dumped or burned, resulting in the loss of valuable material (MENRPD & UNEP, 2020). Although the 2021 Nationally Determined Contribution (NDC) outlines ambitions to compost 60% of organic waste, recycle 15%, establish engineered landfills and expand wastewater treatment across the country, implementation is slow due to conflicts, financial constraints, institutional fragmentation and operational

challenges (NDC 2021). Agro-processing facilities generate residues such as bagasse and filter mud from White Nile's sugar industry, effluents from dairy plants, by-products from oilseed milling and organic sludge from slaughterhouses. These streams remain underused due to weak collection systems, limited treatment infrastructure and low technical capacity. As mentioned earlier, wastewater and industrial effluent are often discharged into unlined pits or surrounding environments, posing environmental and public health risks (Alnali et al., 2013). State-level conditions reflect these national gaps: In White Nile, many communities, especially displaced households, rely on unsafe water sources due to displacement, access constraints, and destruction of infrastructure (ACAPS, 2023). In Gedaref, there is little data on waste volumes or treatment. Research has mostly focused on plastic bag recycling, with limited progress in broader waste management (Geurts, 2000). This gap highlights the need for CBE models that can operate with dispersed, seasonal and variable waste flows.

2.4. Opportunities and Barriers to CBE Adoption

2.4.1. CBE Opportunities

The organic waste profiles of White Nile, Gedaref, and Kassala offer strong entry points for composting, bioenergy, and feed-processing solutions. Agricultural residues, livestock manure, food-processing by-products, municipal organic waste and faecal sludge form a substantial resource base that is currently underutilized (MENRPD & UNEP, 2020; Awad et al., 2017; OCHA, 2022). Their abundance, combined with the states' location in a key agricultural corridor, creates favorable conditions for CBE interventions. These approaches are particularly feasible in conflict-affected areas because they rely on locally available resources, minimizing dependence on long supply chains that are often disrupted during crises. By recovering and reusing water, nutrients, organic matter, and energy from domestic and agricultural waste, CBE interventions can generate value close to where it is needed, reducing the need for transport or external inputs. This localized approach not only supports essential services such as food production, energy, and sanitation but also creates opportunities for livelihoods and community resilience even in contexts with limited infrastructure and restricted access. For humanitarian actors like UNHCR, CBE offers a practical way to complement their operations by providing essential services such as food, energy and sanitation directly within refugee-hosting sites while creating opportunities for livelihoods, peacebuilding and self-reliance.

Bioenergy represents a major opportunity. Biomass already contributes nearly 87% of Sudan's energy supply (Omer, 2018), indicating local familiarity with residue-based fuels. Previous biogas programs also show experience with small-scale digesters (MENRPD & UNEP, 2020). With chronic fuel shortages and unreliable electricity affecting both host and displaced communities, decentralized systems such as household or community digesters, sludge-to-biogas systems and agro-residue digestion could provide cleaner energy while reducing methane emissions. Livestock feed systems present another promising area. Feed shortages are critical in displacement-affected regions, especially in Gedaref and Kassala, where large herds have gathered (FEWSNET, 2023; JRC, 2025; ACAPS, 2024). Residues and post-harvest losses that go unused could be processed into pelletized feed, silage or nutrient-rich blends, reducing pressure on rangelands and lowering household feed costs (Awad et al., 2017). There is also strong demand for soil amendments. Farmers across the three states report declining soil fertility due to shorter fallows, nutrient depletion and variable rainfall (MENRPD & UNEP, 2020). Locally produced compost products can help restore soil structure and moisture retention, offering a viable alternative where fertilizer access is limited or expensive. These opportunities show strong potential to support livelihoods and reduce environmental pressure.

2.4.2. Barriers To Adoption

Despite their potential, several structural barriers limit the growth of CBE enterprises. Transport and logistics challenges are among the most serious, particularly outside refugee camps. While localized resource recovery and short supply chains make CBE feasible within camps, challenges arise when products need to reach markets beyond camp boundaries. Weak road networks, seasonal flooding and fuel shortages make it difficult to move raw materials and finished products, raising costs and reducing competitiveness (ACAPS 2022; OCHA 2023; JRC 2025). Conflict and insecurity along key routes further disrupt supply chains and restrict the movement of people and goods.

Institutional and technical constraints also pose obstacles. Municipal authorities lack equipment, financing and trained staff to run or regulate waste-to-value systems. Many wastewater, faecal sludge, and agro-industrial residue treatment facilities are limited or non-functional (MENRPD & UNEP, 2020; JICA, 2020; Nogod et al., 2020; ACAPS, 2023). Displacement has increased pressure on existing services while disrupting traditional waste-handling practices (JRC, 2025; IOM, 2024). Limited community-level skills in operating digesters, composting facilities or feed-processing technologies further restrict uptake. Financial and regulatory barriers reinforce these constraints. Access to credit is limited, and high upfront costs discourage investment in equipment such as digesters, shredders or pelletizers. Prolonged instability has weakened markets, reduced private-sector confidence and limited access to spare parts and inputs. Regulatory frameworks for waste reuse, sludge management and renewable energy remain fragmented or loosely enforced (MENRPD & UNEP, 2020; NDC, 2021), challenges exacerbated by conflict-related governance disruptions.

Across all three states, waste streams remain poorly quantified, dispersed across rural and peri-urban areas and often too scattered to support predictable recovery. Limited awareness of the economic and agronomic value of organic waste further reduces community participation (MENRPD & UNEP, 2020; Awad et al., 2017; OCHA, 2022). These factors constrain public–private partnerships and limit the potential for scaling CBE models beyond small pilot initiatives. Community acceptance is also a key consideration, particularly where waste recovery or reuse involves materials perceived as unsafe or culturally sensitive. While participatory approaches, awareness-raising, and training have proven effective in similar humanitarian contexts (Njenga et al., 2024a; Gebrezgabher et al., 2025), further research is needed to understand local attitudes in Sudanese camps and host communities.

3. Entry Points for CBE Interventions

Identifying practical, context-specific entry points for CBE interventions that align with humanitarian operational programs and strategies is crucial to meeting immediate humanitarian needs. This section highlights the pathways in which CBE solutions can provide tangible benefits: enhancing access to affordable, reliable energy; restoring soil fertility and boosting agricultural productivity; creating livelihood opportunities; and alleviating pressure on fragile ecosystems. This can support and promote local economic development, enhance recovery and build longer-term resilience. The work builds on the broader methodological framework introduced earlier, where the pathways showcased reflect proven CBE approaches feasible in similar agro-ecological and crisis-affected settings, relevant to conditions in White Nile, Gedaref, and Kassala. Overall, these options stress interventions adaptable to environments with weak formal waste systems, disrupted markets, and limited operational access. They serve as practical starting points for UNHCR and partners working to build resilience through sustainable, locally driven resource recovery systems while improving basic service delivery. The five CBE pathways presented in this section were selected based on their feasibility in fragile and resource-constrained settings, alignment with humanitarian priorities, and proven effectiveness in similar contexts. Each pathway addresses a distinct challenge identified in Section 2, ranging from soil fertility decline and energy shortages to sanitation and waste accumulation issues, while offering immediate opportunities for livelihood support. Together, these entry points provide a practical framework that can guide decision-makers in prioritizing interventions that deliver rapid impact, require minimal infrastructure, and can be scaled progressively as stability improves.

3.1. Food System Resilience through Nutrient Recycling

Building food system resilience in protracted crises requires more than emergency food assistance; it demands strengthening the underlying resource cycles that sustain production over the long term. Resilience frameworks developed in crisis-affected settings emphasize the need to build absorptive, adaptive, and transformative capacities across food and fodder systems rather than focusing only on short-term inputs (Winder Rossi et al., 2017; Eelke & Charleen, 2021). Figure 2 illustrates these interconnected resource flows, showing how biological, economic, social, and governance systems interact to sustain nutrient, water, energy, and material circulation for resilient food systems. In Sudan's displacement-affected states, this means deliberately closing nutrient loops so that organic residues, food waste, and human and animal excreta are treated as resources, rather than liabilities that accumulate in drains and waterways. In these contexts, nutrient recycling could take the form of simple, decentralized systems that convert everyday organic residues into productive inputs for food and fodder production. Small-scale composting of household food scraps, market residues, crop by-products, and animal manure to generate nutrient-rich soil amendments that improve fertility, moisture retention, and crop performance. This is critical in areas with sandy, depleted, or repeatedly cultivated soils without external inputs. Safe, low-cost faecal sludge treatment units can also produce co-compost or pelletized fertilizer suitable for use in home gardens, communal plots, and smallholder fields, reducing reliance on imported fertilizer and mitigating contamination risks around settlements.

Greywater filtration and reuse systems offer another practical entry point, enabling households and community groups to irrigate vegetables, fruit trees, or fodder grasses even when freshwater supplies are limited or disrupted. By supporting home and community gardens, these decentralized solutions reduce the burden on overstretched service systems, lower

input costs, and enable families to maintain or expand food production. These interventions will also improve diet diversity and nutrition by increasing access to fresh fruits and vegetables, contributing to better food security and healthier diets despite market instability. Importantly, nutrient recycling interventions, such as compost production, seedling nurseries, the sale of soil amendments, and local distribution networks, also create livelihood opportunities, particularly for women and youth.

Global assessments of sustainable food systems emphasize that biomass, nutrients, and organic side streams must be increasingly recycled at local and regional scales to reduce reliance on external fertilizers and mitigate ecological pressures (Freibauer et al., 2011; Buller et al., 2024). Circular food and sanitation initiatives similarly demonstrate the potential of reintegrating biodegradable materials and organic waste, from food residues and crop by-products to paper, packaging and sanitation-derived nutrients, into biological cycles through composting, anaerobic digestion, black soldier fly processing and other resource-recovery technologies. (FAO & Toilet Board Coalition, 2021; Morel & Diener, 2006). Such systems can divert significant organic fractions from landfills and open dumps while supplying IDPs and host communities with beneficial bio-inputs.

Evidence suggests that in White Nile, Gedaref, and Kassala, protracted conflict and climate shocks intersect with already nutrient-poor soils, degraded rangelands, and high dependence on imported fertilizer (FAO, 2023). Recycling nutrients from municipal organic waste, market residues, agro-processing by-products, and sanitation streams can help rebuild soil organic matter, improve water-holding capacity, and stabilize yields in both smallholder fields and camp-based or peri-urban gardens (FAO, 2023). Linking circular sanitation and livestock feed processing into a coherent nutrient-recycling strategy allows multiple waste streams to feed into a common pool of soil-improvement products. This, in turn, can reduce exposure to fertilizer price spikes and supply disruptions, while lowering environmental burdens from indiscriminate dumping and discharge.

Nutrient-recycling interventions also create opportunities for inclusive enterprise (Somorin et al., 2025a). Community-run composting sites, small-scale biofertilizer producers, cooperatives that aggregate and process crop residues, and micro-enterprises that manufacture biodegradable consumer items designed to return to the soil can all emerge as part of a broader CBE. When combined with participatory planning, gender-responsive approaches, and locally driven innovation, such activities contribute to longer-term resilience pathways and support social cohesion between displaced and host communities (Betts et al., 2015).

a-b

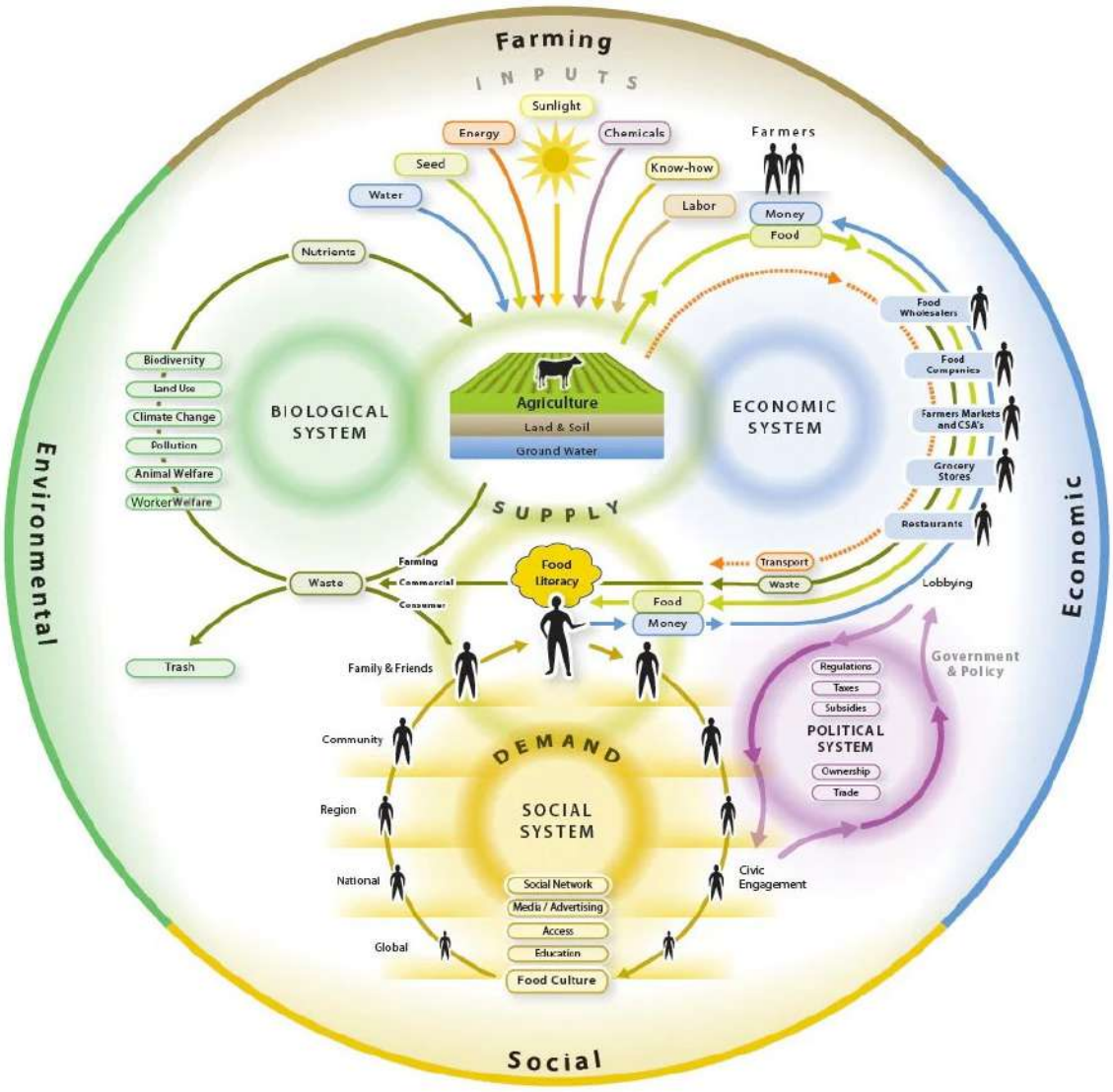

Figure 2: *Circular food system illustrating how inputs, supply chains, consumer behavior, and resource recovery interact across environmental, economic, social, and governance domains, to support more resilient and circular food system outcomes.*

Image Source: 2025, Circular Harvest

3.2. Bioenergy Generation

Bioenergy generation offers a practical, scalable opportunity to convert sanitation, agricultural, and organic market residues into useful energy services in displacement-affected regions. In humanitarian settings where fuel scarcity, high diesel dependence, and unreliable grid electricity undermine basic services, renewable energy solutions derived from local biomass can enhance self-reliance, reduce operational costs, and strengthen community resilience. Evidence from Ethiopia, Kenya, Jordan, Burkina Faso, and Uganda shows that decentralized bioenergy systems, such as small biogas digesters and waste-to-fuel briquetting units, have been successfully deployed to support cooking, lighting, and institutional energy needs in displacement settings (Lahn & Grafham, 2015; IRENA, 2019; Somorin et al., 2025b-c)

Energy assessments consistently identify diesel use as a major cost burden for camps, clinics, water pumping, and humanitarian operations, with these costs often absorbed by humanitarian agencies and host governments. The Chatham House Report shows that reliance on inefficient generators drives high costs, unreliable power, and increased carbon emissions (Lahn & Grafham, 2015). In response, the sector has seen a growing push to "green" camps and humanitarian operations through renewable energy and low-carbon infrastructure, led by initiatives such as the Global Platform for Action on Sustainable Energy in Displacement Settings and UNHCR's Global Strategy for Sustainable Energy (GPA, 2022; UNHCR, 2019). Beyond service delivery, CBE embeds humanitarian energy systems within national climate frameworks, directly contributing to NDCs and National Adaptation Plans (NAPs) through emissions reduction, waste diversion, ecosystem restoration, and green job creation. This alignment positions displacement settings as legitimate sites for climate action, opening access to climate finance, carbon markets, and blended funds (Bodach et al. 2024).

In parallel, host communities and displaced households frequently resort to unsustainable charcoal and firewood collection (IRENA, 2019), driving deforestation, land degradation, and protection risks for women and girls. Resource-recovery bioenergy displaces these fuels by transforming faecal sludge, manure, food residues, and agro-by-products into clean energy. For example, biogas systems, ranging from household-scale units to institutional digesters, have shown strong performance in community schools, health clinics, or communal kitchens. FAO guidance notes highlight that they can meet household cooking needs while reducing exposure to smoke and eliminating the need for wood fuel (FAO, 2019; FAO, 2021). In Ethiopia and Kenya, camp-based digesters have been used to produce gas for communal kitchens and sanitation blocks, improving safety and reducing operational costs for agencies. Similarly, briquetting initiatives in Uganda, Kenya, and Tanzania have demonstrated the viability of converting agricultural residues into clean-burning briquettes (Lahn & Grafham, 2015).

Bioenergy systems also serve broader resilience and operational functions. IRENA's assessment of refugee settlements in Iraq and Ethiopia highlights that renewable energy sources, including biomass, can support electricity needs for health centers, water pumping, and small enterprises when integrated with solar mini-grids and hybrid systems (IRENA, 2019). Waste-to-energy reduces unmanaged waste and hygiene risks while producing useful co-products. When designed with communities, these systems create livelihood pathways across collection, sorting, feedstock supply, digester construction, briquette production, and energy service provision. Women and youth in particular can benefit from new roles in processing, marketing, and maintenance. Several systemic barriers limit the widespread adoption of bioenergy in humanitarian contexts. Short humanitarian funding cycles, inadequate maintenance budgets, and the absence of long-term capital investment frameworks undermine the sustainability of bioenergy solutions (GPA, 2022; NRC, 2022). For

example, the State of the Humanitarian Energy Sector (SOHES) report highlights that energy projects often fail due to unclear ownership, a lack of technical capacity, and the absence of multi-year financing needed for ongoing operations and maintenance (GPA, 2022). Private-sector actors, who could support energy-as-a-service models, manufacture components, or provide distribution networks, face barriers such as restrictive procurement processes, limited access to camp-level data, and high perceived risk (Van Landeghem, 2016). Blended-finance mechanisms, payment-by-service models, and public–private partnerships are therefore essential for scaling renewable energy systems in fragile settings (GPA, 2022). Box 1 illustrates how CBE opportunities translate into practice, showcasing adaptable bioenergy models for cooking fuel and institutional energy services.

Box 1: Turning Waste into Clean Energy in Kakuma Refugee Camp in Kenya

Figure 3: *Briquette production in Kakuma Refugee Camp, Turkana, Kenya. Left: Mechanical press producing briquettes from treated sludge and waste biomass. Right: Drying of briquettes (source: Sanivation)*

Kakuma Refugee Camp and the adjacent Kalobeyei Settlement in Turkana County together host over 240,000 refugees, with 198,345 in Kakuma and 55,074 in Kalobeyei as of March 2023 (Njenga et al., 2024b). These communities face chronic energy shortages for cooking and severe pressure on surrounding dryland ecosystems. Firewood and charcoal remain the primary cooking fuels. Yet, UNHCR's firewood distribution covers only a fraction of household needs, forcing up to 95% of refugee households to exchange food rations for cooking fuel and exposing women and girls to protection risks during firewood collection. These dynamics have intensified resource-related tensions between refugee and host communities, and have underscored the urgent need for cleaner, locally produced, and affordable cooking energy alternatives. Recognizing this challenge, UNHCR and the Bill & Melinda Gates Foundation partnered with Sanivation to pilot an innovative waste-to-value sanitation and fuel system in Kakuma (Figure 3). The project installed 500 container-based toilets in areas with challenging ground conditions and established a treatment facility capable of thermally sanitizing two tons of faecal sludge per day (UNHCR, 2020). The treated sludge was then blended with charcoal dust and molded into high-performance briquettes that burned longer and produced less smoke than traditional charcoal, while offering a safe reuse pathway for human waste. Over three years, the system treated more than 250 tons of faecal sludge and produced over 150 tons of briquettes. User acceptance was high: two-thirds of refugees surveyed expressed a willingness to purchase the briquettes, which were viewed as cost-effective and efficient for cooking (UNHCR, 2020). A complementary initiative in the nearby Kalobeyei Settlement trained refugee and host-community women to produce charcoal briquettes from readily available waste biomass, including charcoal dust and the invasive shrub *Prosopis juliflora* (Njenga et al., 2024b). Women reported that briquettes reduced fuel expenditures, alleviated the need to trade food rations for firewood, and lowered the risks and burdens of firewood collection. The briquettes' slow, steady burn made them suitable for long-duration cooking tasks, while the training provided new livelihood opportunities and strengthened women's agency in household energy decisions. These experiences demonstrate the potential for bioenergy systems in humanitarian settings: transforming organic waste into affordable cooking fuel; reducing environmental degradation and deforestation; improving health and safety; and creating income-generating activities for displaced and host communities. These models highlight how resource recovery can reduce vulnerability in protracted displacement contexts.

3.3. Feed for Displaced Animals and Livestock Populations

Livestock remain a critical livelihood asset for both displaced and host households in Sudan, providing milk, meat, manure, transport, and a key store of wealth during prolonged instability. However, conflict-driven displacement, recurrent dry spells, and disrupted market access have exacerbated chronic feed shortages (FEWSNET, 2023; JRC, 2025; ACAPS, 2024). National evidence indicates that Sudan's livestock feed base is fundamentally constrained: rangelands are losing productivity, crop residues are coarse and nutritionally poor, and existing feed supply systems cannot meet demand. Wilson (2018) underscores this challenge, noting that livestock feed often falls short of requirements and that both natural forage and crop by-products are typically low in nutritive value, leading to chronic underfeeding and reduced animal performance. These pressures increase the risk of livestock loss for displaced households and constrain their ability to recover after shocks.

CBE approaches offer several practical opportunities to expand feed availability using locally sourced materials that are often underused or wasted. Large quantities of crop residues, such as sorghum stover, groundnut haulms, sesame stalks, and pulse residues, are widely available following harvest seasons but are seldom processed into higher-value feed. FAO's technical guidance demonstrates that simple techniques such as chopping, soaking, urea treatment, or microbial enrichment can significantly improve digestibility and nutritional content, making these materials suitable for goats, sheep, and cattle in low-input systems (FAO, 2016). In urban and peri-urban market centers and agro-processing hubs, by-products such as oilseed cakes, fruit pulp, brewery waste, rice bran, cassava peels, and broken grains can be safely converted into balanced feed mixes through small-scale formulation units. These materials can be transformed into pelletized feed, nutrient-rich blends, haylage or silage, providing practical ways to stabilize feed availability in both dry and rainy seasons (Molina-Flores et al., 2020). However, the main constraints to scaling these solutions are linked to limited local processing capacity, particularly the lack of milling, chopping, and storage infrastructure required for consistent feed production (Wilson, 2018).

Biological circular systems further expand this feed potential. Black soldier fly (BSF) larvae offer a high-protein, low-cost feed ingredient that can be produced from organic waste streams. A recent UNHCR-supported initiative in Tongogara refugee settlement in Zimbabwe demonstrates the strong livelihood potential of insect farming: refugees trained to rear BSF use the larvae to supplement poultry diets, improving weight gain, reducing feed costs, and generating income from surplus birds and larvae (UNHCR, 2024). The benefits of such local feed innovations are significant: low land requirements, minimal water use and low start-up costs. Affordable, consistent feed reduces vulnerability to price shocks, helps households retain productive livestock during crises, and accelerates recovery once conditions stabilize.

For many displaced families who rely on small ruminants as their primary assets, improved access to feed directly enhances income stability and food security. Repurposing crop residues, organic waste, and insect bioconversion systems also reduces pressure on degraded rangelands, mitigates waste accumulation in settlements, and strengthens linkages between agriculture, waste management, and humanitarian support systems. It can also foster cooperation between refugees and host communities, particularly important when food scarcity intensifies competition over grazing areas and shared natural resources (FAO, 2016). Community-based or cooperative feed-processing hubs can reduce grazing pressure, improve herd productivity, and provide employment in collection, processing, storage, and distribution. Realizing the full potential of such biological systems will, however, require targeted support for training, materials, and basic infrastructure to ensure that production can be sustained under the region's harsh climatic and logistical conditions. The experience highlighted in Box 2 reinforces the practical viability of these biological approaches. It shows how refugee communities, even in highly resource-constrained settings, can convert small volumes of organic waste into high-value protein for poultry and small livestock.

Box 2: Insect Farming as a Livelihood Strategy in Tongogara Refugee Settlement, Zimbabwe

According to UNHCR (2024), an innovative insect-farming initiative in the Tongogara settlement in south-eastern Zimbabwe is transforming how displaced households secure food, income, and dignity. Since 2022, UNHCR, in partnership with the World Bank and Chinhoyi University of Technology, has supported refugees and members of the host community in rearing BSF larvae using organic waste, such as vegetable scraps. The larvae, rich in protein and easy to produce with minimal water, land, or equipment, serve as a cost-effective substitute for commercial poultry feed. For many refugees, the shift to BSF farming has been life-changing. Francine Mashimango, who fled conflict in the Democratic Republic of the Congo with her nine children, now raises flies and harvests larvae daily (Figure 4). By incorporating BSF larvae into chicken feed, she has reduced production costs, improved growth rates, and expanded her income through the sale of birds. Francine describes the work as restoring a sense of purpose and self-reliance after years of uncertainty, noting that "when you are involved in a project like this, it encourages you to work harder because you don't want to depend on assistance." Beyond individual gains, the initiative fosters collective resilience. Refugees and host community members can train and work together, strengthening social cohesion in a settlement that hosts over 16,000 people from several neighboring countries. The system also contributes to environmental sustainability by converting organic waste into valuable inputs for livestock and soil fertility. Although extreme temperatures occasionally threaten fly survival, participants are learning adaptive techniques to manage heat stress. BSF farming illustrates how circular, low-cost solutions can enhance livelihoods, food security, and climate resilience in displacement-affected settings.

Figure 4: *Francine feeds her chickens with maggots from the black soldier flies in her yard at Tongogara. Source: UNHCR, 2024 (photo: Hélène Caux/UNHCR)*

3.4. Small-Scale Wastewater Reuse and Greywater Irrigation

Small-scale wastewater and greywater reuse systems have proven to be powerful resilience-building interventions in water-stressed, fragile, and conflict-affected environments. Experiences from Ethiopia, Jordan, and the Sahel illustrate how simple filtration and reuse systems can stabilize household water access and security, while reducing environmental health risks and strengthening the ability of communities to cope with climatic and service-related shocks (Morel & Diener, 2006; Bakker & Boelee, 2013; Surani, 2003; Rohling et al., 2023; Van de Walle et al., 2023). In Ethiopia, for example, keyhole and vertical greywater gardens enabled households to maintain vegetable production during drought by filtering kitchen and wash water through layered organic and gravel systems, improving both water-use efficiency and household nutrition while limiting wastewater accumulation around homes (Bakker & Boelee, 2013). Similarly, long-running pilots in Jordan demonstrated that gravel-filtered and modified septic-based greywater units enabled families to irrigate fruit trees and home gardens despite chronic water scarcity, supporting later revisions to national greywater guidelines (Surani, 2003). In the Sahel, rainwater harvesting and retention systems continue to buffer households against seasonal drought, lower pressure on shallow aquifers, and support basic domestic and productive water use (Rohling et al., 2023).

These lessons are highly pertinent to White Nile, Gedaref, and Kassala, where many displaced and host-community households depend on shallow wells, seasonal streams, and overextended piped networks that frequently fail during peak demand or conflict-related disruptions. At the same time, significant volumes of household greywater, market wastewater, and partially treated effluent are discharged untreated into drains and open areas, creating health hazards rather than supporting productive use (OCHA, 2022; UNHCR, 2025 a-b). Introducing low-cost systems such as perforated sand-and-gravel filters, decentralized constructed wetlands, greywater towers, or container-based irrigation can convert these underutilized flows into reliable inputs for small gardens, camp plots, and peri-urban food production. Experience from Ethiopia's MUStRAIN program and related greywater tower and keyhole garden initiatives shows that simple filtration and soil-based systems can safely use greywater to enhance water-use efficiency, support vegetable cultivation, and improve dietary diversity where access to nutritious foods is constrained (Bakker & Boelee, 2013).

Beyond water access, small-scale reuse systems deliver important environmental and health co-benefits. Properly designed greywater and rainwater systems reduce stagnant wastewater around shelters, lower mosquito breeding and contamination risks, and decrease pressure on already strained freshwater sources (Morel & Diener, 2006; Rohling et al., 2023). The global review by Morel & Diener (2006) highlights adaptable household- and neighborhood-scale options, from infiltration trenches to planted soil filters, that improve sanitation while enabling productive irrigation. Recent work by Van de Walle et al. (2023) further emphasizes that local reuse of segregated greywater can enhance the resilience and adaptability of water systems by reducing dependence on long-distance water transfers and centralized infrastructure. Importantly, low-energy and gravity-fed designs demonstrated in Ethiopia, Jordan, and the Sahel operate reliably even during power outages, fuel shortages, or infrastructure disruptions (Surani, 2003; Bakker & Boelee, 2013). Box 3 reinforces these lessons, showing how greywater-fed keyhole gardens in western Tanzania enabled refugee households to grow diverse vegetables year-round, improve nutrition, and reduce stagnant wastewater (Drechsel, 2024). Such decentralized safe water reuse approaches demonstrate how localized water solutions can strengthen household resilience while laying the foundation for broader CBE interventions across sanitation, agriculture, and small-scale enterprise development. By reframing waste streams as resources, the circular sanitation economy not only improves public health and environmental outcomes but also creates economic opportunities.

Box 3: Greywater-Fed Keyhole Gardens in Tanzanian Refugee Camps

Refugee camps in western Tanzania provide one of the clearest documented examples of greywater reuse integrated into humanitarian food security programmes. As highlighted in Drechsel (2024), more than 1,300 refugee households participated in a joint UNHCR–Danish Refugee Council initiative that promoted keyhole gardens as a low-space, low-water method for vegetable production (Figure 5). These raised circular beds, constructed from locally available stones, soil, ash, compost and a central woven basket, were specifically designed to make productive use of household greywater from washing and food preparation. The greywater, poured into the central basket, slowly filtered through layered organic material, providing moisture and nutrients while avoiding direct contact with edible crops, an essential safety feature in crowded humanitarian settings. The gardens required minimal land and could produce food year-round, even under high temperatures and limited freshwater supply. According to program reports, households grew at least 5 types of vegetables and produced enough to "feed a family of eight," significantly improving dietary diversity and reducing reliance on external food aid. For many refugees, particularly women, who were the primary managers of the gardens, these systems delivered benefits beyond food. The initiative improved nutritional status, strengthened self-reliance, and restored dignity to families facing protracted displacement. Keyhole gardens also helped reduce stagnant greywater around shelters, lowering risks of vector-borne diseases and improving environmental conditions within the camp. This case demonstrates that simple greywater reuse technologies, when paired with risk-aware design and community involvement, can meaningfully improve food security, wellbeing, and environmental health in fragile settings.

Figure 5: *A keyhole garden in a resettlement village (Image source: Esther Havens, as cited in (Drechsel, 2024)).*

3.5. Strengthening Local Value Chains and Microenterprise Development

Localizing the production and distribution of consumer-oriented bio-products offers a practical pathway to expand livelihood opportunities while reducing dependence on imported goods in displacement-affected areas. Across White Nile, Gedaref, and Kassala, there is an indication of substantial volumes of plant-based fibres, paper residues, packaging waste, agricultural by-products, and organic materials that can be transformed into everyday products in demand from both humanitarian agencies and local markets. Building bioproduct value chains locally is a viable entry point for microenterprise activity, delivering strong livelihood and supply chain benefits. Basic consumables such as food packaging, cups, plates, hygiene products, cleaning supplies, and temporary shelter materials are in constant demand in camps and host communities. Yet most are currently imported, fossil-based, and contribute to mounting plastic waste. When community enterprises produce bio-based alternatives, such as molded pulp plates, biodegradable food boxes, reusable menstrual products, compostable bags, bio-based soaps and detergents, they not only reduce procurement costs and waste burdens but also generate employment and income for crisis-affected households.

Youth and women's groups are particularly well-positioned to lead such enterprises due to low entry barriers, the availability of local feedstocks, and close alignment with existing skills among those already participating informally in waste handling, small-scale processing, food preparation, and local trade. The resilience benefits of this approach are also substantial. By anchoring income generation in locally available materials and simple, decentralized production systems, households become less vulnerable to market disruptions, supply chain interruptions, or fluctuations in the prices of imported goods. Locally produced bio-products also diversify livelihood options in settings where formal employment is scarce, ensuring that displaced and host communities can sustain income even during crises. These enterprises can also be deliberately integrated with climate-smart crop production systems and restoration efforts to secure a sustainable supply of bio-feedstocks while preventing maladaptation. For example, banana stems, and other agro-residues offer renewable inputs for molded fibre products, packaging materials, and compostable containers. Establishing small community woodlots, bamboo plots, or agroforestry systems ensures that enterprises relying on fibre, pulp, or biomass do not drive deforestation or further degrade fragile landscapes. Box 4 illustrates the practical potential of this approach, showing how the Anandi Eco+ mini-factory model enables women's cooperatives to convert agricultural fibres into fully compostable hygiene products using simple, decentralized machinery. The example demonstrates how locally available residues can anchor viable enterprises, reduce dependence on imported disposables, and generate dignified, consistent income for women and youth. It also highlights the broader circular benefits of such initiatives: they replace fossil-based products, reduce waste accumulation, and embed regenerative material flows within local economies.

Strengthening local value chains requires support across material preparation, processing, quality control, branding, and distribution. Training in product design, hygiene and safety standards, and eco-labelling improves consumer confidence, while linking producers to humanitarian procurement systems, school feeding programs, community kitchens, and local retailers creates steady, predictable markets. Technical assistance, including access to basic equipment (presses, moulds, small shredders), business skills training, and linkages to local retailers or humanitarian procurement systems, can help these activities evolve into viable enterprises. Overall, nurturing local value chains lays important groundwork for post-conflict recovery. As markets re-open and mobility improves, communities with established CBE enterprises are better positioned to integrate into expanding regional trade networks, supply nearby towns, or link with larger agro-processing actors. The skills, social networks and local capital accumulated through small-scale CBE businesses can accelerate economic recovery, strengthen social cohesion and reinforce community agency.

Box 4: The Anandi Eco+ Model for Compostable Sanitary Pads

The Anandi Eco+ initiative, developed by Aakar Innovations, provides a compelling example of how decentralized, bio-based manufacturing can create dignified livelihood opportunities in low-resource contexts while addressing persistent hygiene and waste challenges (Anandi Eco+, 2026). The pads (Figure 6) are made entirely from agricultural fibers such as banana stem, jute, and hemp, offering a fully compostable alternative to the plastic-based menstrual products that dominate global markets and contribute significantly to solid waste burdens. Central to the model is the Aakar "Mini-Factory", a small, semi-automated production unit that can be established and operated by women's cooperatives or youth groups. Each unit typically employs 8–12 workers and uses simple machinery that can run on intermittent power, making it well-suited to rural, peri-urban, and humanitarian environments. Raw materials are sourced locally, production processes are easy to learn, and finished products can be distributed to schools, clinics, community vendors, and humanitarian partners. Beyond providing affordable menstrual hygiene products, the mini-factory model has generated measurable social and economic benefits. Participating women gain steady income, improved business skills, and enhanced agency over local hygiene provision. Communities benefit from reduced dependence on imported disposables, while the compostable nature of the pads helps to reduce waste accumulation in areas with limited disposal infrastructure. For displacement-affected regions, this model demonstrates how simple processing of plant-based residues can create livelihood opportunities for women and youth while embedding circular material flows within local economies.

Figure 6: *Compostable Sanitary Pads (image source: Anandi Eco+, 2026)*

3.6. Circular Sanitation for Safe Containment, Treatment and Productive Reuse

Sanitation-related waste streams, such as faecal sludge, wastewater, greywater, and solid waste from household pits, communal latrines, markets, and emergency facilities, pose a persistent burden on service providers, humanitarian organizations, and communities (UN-Habitat, 2024). When unmanaged, these waste streams accumulate in drains and open spaces, overwhelming limited infrastructure and leading to environmental pollution and public health risks. Circular sanitation offers a practical pathway to close these gaps by linking safe containment, affordable desludging and treatment, and productive reuse of sanitation by-products. The Toilet Board Coalition describes this integrated approach as a circular sanitation economy (CSE), a model in which sanitation systems generate value through nutrient capture, energy recovery, and the creation of usable end-products such as fertilizer, biogas, briquettes, insect-based feed, and treated water for non-potable reuse (FAO & Toilet Board Coalition, 2021). In crisis-affected areas, where infrastructure is fragmented and resources are scarce, CSE models offer a scalable, decentralized approach to improving public health while supporting livelihoods. This is particularly relevant to White Nile, where latrine ratios exceed emergency standards and effluent discharge from agro-industrial facilities already burdens water bodies. Decentralized faecal sludge treatment combined with composting or biogas systems could reduce contamination loads and supply nutrient-rich soil amendments for nearby farms. In Gedaref, where cholera and other waterborne diseases are linked to stagnant wastewater and overflowing latrines, community-scale sludge processing units could minimize groundwater pollution while creating local enterprise opportunities. In Kassala's flood-prone areas, raised sanitary containment, lined pits, and mobile desludging services can prevent latrine collapse during the rainy season while supporting the recovery of organic by-products for fuel or soil restoration.

Applying this model in these contexts highlights clear opportunities to shift away from traditional sanitation practices toward regenerative systems that reintroduce resources such as treated wastewater, nutrients, and biomass into local economies. Once by-products are safely treated and processed, they can re-enter humanitarian and host-community economies through a wide network of buyers. For example, treated effluent can support smallholder irrigation, communal gardens, and environmental restoration; organic fertilizers can reduce input constraints for displaced and host farmers; bioenergy products can supply households, communal kitchens, and micro-enterprises; while protein-rich biomass can feed small livestock, aquaculture units, and school-feeding garden programs. Innovative sanitation-derived materials can support local manufacturing and livelihood initiatives. Even in resource-limited settings, decentralized, low-tech solutions can transform sanitation products for local or community use. This presents various entrepreneurial opportunities, including waste and sludge collection, transport and logistics services, decentralized treatment operations, compost production, biogas management, and product distribution. These services can be provided by small local operators or community groups, including youth and women-led enterprises. Such enterprises can generate income locally by utilizing available waste streams, leveraging existing labor, and creating demand for soil amendments or renewable energy products. Incorporating circularity into the sanitation chain can reduce inefficiencies and strengthen essential services. Circular sanitation thus represents a multi-benefit opportunity: it strengthens public health protection while enabling the emergence of new livelihood activities across desludging services, compost production, briquette manufacturing, and local fertilizer markets. With appropriate governance, training, and partnerships, particularly with women and youth-led microenterprises, CSE models a major humanitarian service burden into a productive, resilient, and locally grounded value chain. Figures 7-8 illustrates this model by mapping how biological waste inputs move through containment, collection, treatment, and resource recovery processes to generate valuable end products.

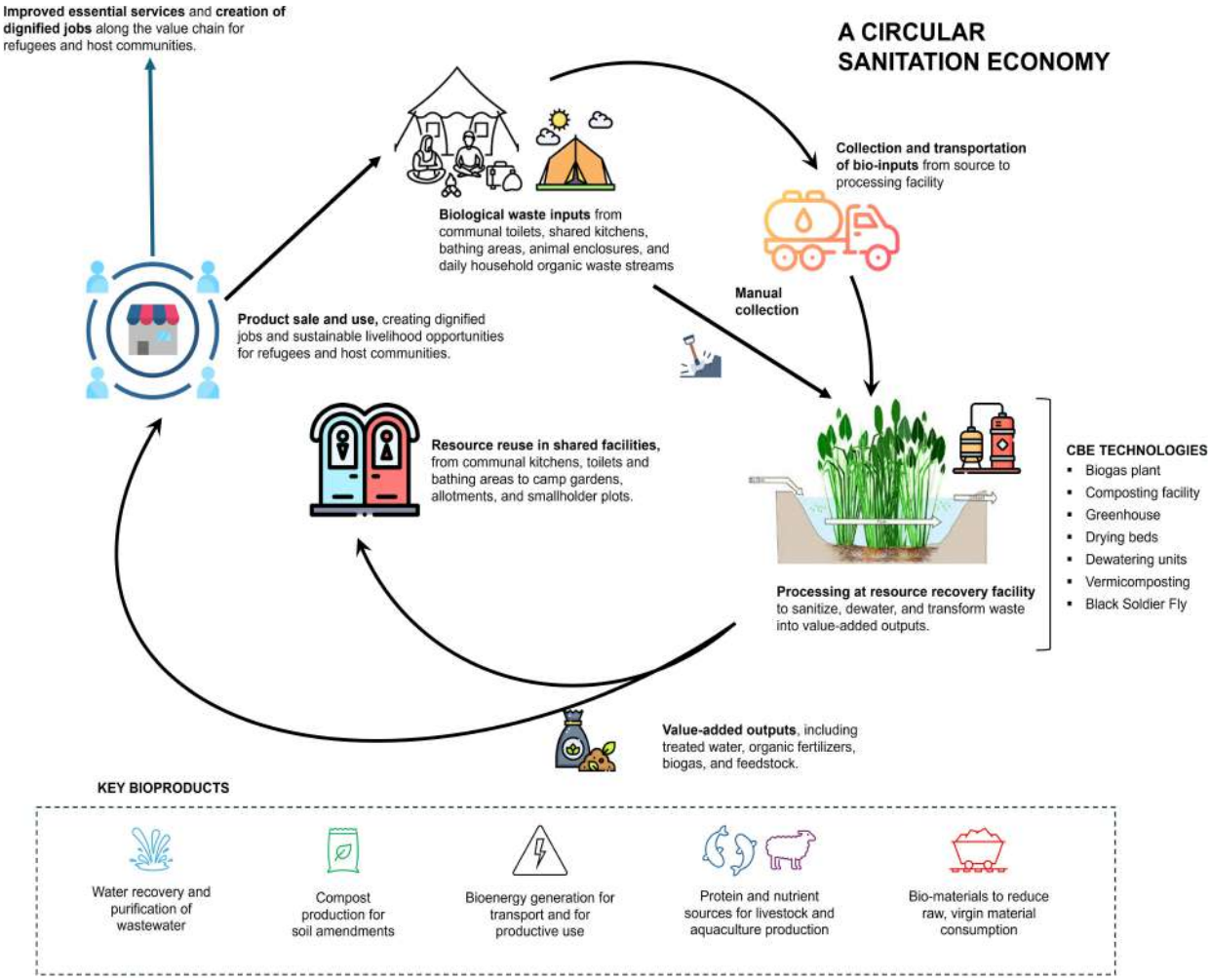

Figure 7: A Circular Sanitation Economy for Refugee and Host Communities Image
Source: Toilet Board Coalition (modified)

4. KEY IMPERATIVES FOR CBE IMPLEMENTATION

This report has shown that displacement-affected areas in White Nile, Gedaref, and Kassala face mounting pressures from overstretched water and sanitation systems, degraded soils, limited access to agricultural inputs, and growing challenges posed by organic waste. Although the total amount of waste generated in these locations has not yet been quantified, secondary evidence indicates that even small, diffuse streams of organic waste, crop residues, and greywater, when unmanaged, contribute to environmental health risks and place additional burdens on already strained services. CBE approaches provide a practical framework for turning these unavoidable by-products of daily life into useful resources that can support food production, reduce local contamination, and create targeted livelihood opportunities. The following imperatives outline how UNHCR and development partners can integrate CBE principles into humanitarian planning to strengthen essential services, improve household wellbeing, and build more resilient, locally grounded systems.

Integrate CBE principles into settlement planning and humanitarian service delivery.

Humanitarian responses in Sudan typically focus on meeting immediate needs, yet the pressures on land, water, waste, and energy systems require a shift toward designs that anticipate long-term displacement. Embedding CBE principles, such as integrating garden spaces, small-scale composting sites, greywater reuse systems, and opportunities for resource recovery, into camp layouts and service upgrades can reduce future burdens on WASH, food security, and energy provision. This can be achieved by allocating micro-plots for gardening from the outset. In existing, dense settlements, space-efficient systems such as vertical sacks, trellises, and multilayer beds can be co-developed with refugee committees, so gardening becomes part of core site planning, not an add-on. Gardening and CBE interventions should be linked to nutrition programs: targeting households with young children, pregnant and lactating women, and people with chronic illnesses, and pairing gardening with nutrition education and cooking demonstrations. This shift ensures that even small flows of recoverable materials are mobilized to improve living conditions, support basic health and nutrition, and strengthen household resilience over the long term.

Establish decentralized organic waste recycling hubs to reduce environmental risks and improve essential services.

Uncollected organic waste, market residues, and poorly managed sanitation by-products contribute to contamination and public health risks in settlements and host communities. Small, decentralized resource recovery hubs for co-composting, fuel briquetting, or feed preparation can convert diffuse waste streams into useful products that support soil improvement, cleaner cooking, or small-scale agriculture. Such systems can significantly ease pressure on limited waste-handling infrastructure while improving safety and environmental conditions. Household and community gardens should be explicitly connected to resource recovery infrastructure. For example, compost products can be used in household and community gardens; low-tech greywater systems can provide safe water reuse for irrigation; and packaging waste can be used to make grow bags, trellis materials, or irrigation components. This creates visible nutrient loops and reduces pressure on surrounding ecosystems. To achieve this, CBE interventions should prioritize scalable, modular, and easy-to-maintain technologies and practices, enabling systems to expand gradually and be replicated across different settlement types without requiring specialized equipment or high

technical inputs. Ensuring long-term functionality also depends on strengthening local capacity for routine operation and maintenance, with practical training that enables community members, cooperatives, and local authorities to manage systems confidently and reliably. Inclusive governance is equally important: engaging women, youth, and vulnerable groups in decision-making and day-to-day management helps anchor CBE systems within the community and ensures benefits are equitably shared.

Strengthen CBE enterprises to expand livelihood opportunities and self-reliance.

Where feasible, viable resource-recovery hubs can be turned into micro-enterprises, offering income, dignity, and skills development. Other enterprises can be supported or strengthened, such as seedling production, compost sales, vertical garden installation, simple feed mixing, and eco-product fabrication, to reduce aid dependency and diversify local economies. Supporting women and youth as facilitators and operators of these initiatives enhances inclusion and ensures that CBE activities reflect local priorities and capabilities. Support should go beyond agro-inputs (seeds, fertilizers) to starter kits (simple tools, simple irrigation), bundled with intensive practical training; small grants or revolving funds for micro-enterprises in compost sales, seedling production, vertical garden installation, poultry, and fuel-efficient stove fabrication; market access support (stall rentals, aggregation points, links to host-community markets). Training should also go beyond technical skills in converting waste into value-added products and expand to include business models, such as how to form cooperatives, record-keeping, pricing, customer relations, and group governance, to ensure that enterprises can operate sustainably over time.

Build partnerships that connect humanitarian actors, local authorities, and market systems.

Stronger coordination among humanitarian agencies, municipal authorities, cooperatives, and small businesses is essential to maintain recovery hubs, ensure the responsible handling of organic materials, and create channels for CBE products to reach local markets. These partnerships also help align humanitarian programming with state-level development strategies, improving sustainability and cost-effectiveness. To achieve this, development agencies can expand multi-stakeholder coalitions that bring together municipal authorities, camp management, farmer groups, women's cooperatives, and private enterprises to jointly plan, operate, and monitor resource-recovery, and reuse systems. Such partnerships enable shared ownership, strengthen governance, and create pathways for community enterprises to emerge around input supply, production and distribution. To support prioritization and investment, these coalitions should be backed by clear evidence on performance, costs, and local demand for CBE products, enabling decision-makers to identify which interventions offer the most viable and scalable benefits. This can be achieved by rapid assessments of waste streams, service gaps, and market conditions, complemented by demonstration pilots and participatory monitoring to understand what works under different local constraints.

Invest in skills, safeguards, and enabling infrastructure for sustained CBE uptake.

For CBE interventions to function reliably, communities need practical skills in waste handling, compost quality control, small-scale production techniques, and basic enterprise management. To ensure environmental and public health safeguards, agencies should facilitate basic infrastructure upgrades, including controlled waste sorting zones, improved drainage around RRR facilities, and simple pre-treatment units for sanitation sludge. Simple infrastructure, such as waste-sorting areas, drainage improvements, and low-tech greywater pre-treatment systems, can provide the foundation for safe, scalable implementation. Such investments protect public health while strengthening the quality and acceptance of resource-recovered products. Furthermore, CBE activities should be designed to reduce protection risks and strengthen social cohesion. Agroforestry and fuel-efficient stoves can reduce fuel consumption and associated carbon-emission risks; shared seed banks, garden competitions, and co-managed community plots can build trust between displaced and host communities. Targeted training for youth and women in safe waste handling, compost quality control, feedstock preparation, business management, and marketing can transform CBE activities into viable livelihood pathways and longer-term economic participation.

Position CBE interventions as climate investments aligned with NDCs and NAPs.

CBE interventions in displacement settings, including waste-to-energy, composting, greywater reuse, and climate-resilient food production, directly contribute to national mitigation and adaptation priorities by reducing emissions from open dumping and biomass use, restoring soils, lowering deforestation pressure, and strengthening climate-resilient livelihoods. Framing these activities as contributions to Sudan's NDC and NAP enables humanitarian investments to be embedded within national climate strategies rather than treated as stand-alone projects. This alignment creates pathways to access international climate finance, including the Green Climate Fund, Adaptation Fund, bilateral climate windows, and emerging results-based mechanisms such as carbon and waste credits, while also supporting UNHCR's climate action objectives for sustainable energy, waste management, and resilience in displacement settings (UNHCR, 2024; GPA, 2022). By structuring CBE pilots as bankable, modular climate actions with measurable mitigation and adaptation benefits, agencies can leverage humanitarian budgets as catalytic capital in development and climate finance, ensuring continuity beyond short funding cycles and enabling scale across settlement typologies (Mendum et al., 2024).

These imperatives provide a practical roadmap for embedding CBE practices into humanitarian response and recovery efforts, enabling agencies to improve essential services, strengthen livelihoods, and support resilient and environmentally sustainable settlements.

Table 1: Roles and responsibilities of key actors in scaling decentralized CBE solutions

Actors	Roles and responsibilities
UNHCR and Humanitarian Actors	▪ Integrate CBE approaches into settlement planning. ▪ Provide catalytic funding for low-tech treatment units. ▪ Coordinate partners to ensure safe waste handling. ▪ Support capacity building for youth and women. ▪ Embed CBE models into WASH, energy, and livelihoods programming.
State and Local Governments	▪ Create enabling policies for waste reuse. ▪ Allocate land for treatment sites and strengthen regulatory oversight. ▪ Facilitate partnerships with private operators. ▪ Ensure interventions align with national-/state-level developmental, environmental and agricultural priorities.
Communities, Cooperatives, and Enterprises	▪ Operate decentralized waste-to-value systems. ▪ Manage collection and transport services. ▪ Operate and maintain resource recovery facilities and/or microenterprises. ▪ Support CBE mainstreaming, awareness and capacity building. ▪ Participate in monitoring and revenue-sharing mechanisms.

5. CONCLUSION

This report set out to identify practical CBE entry points to strengthen resilience and livelihoods in three Sudanese states affected by displacement. Findings show that conditions in White Nile, Gedaref, and Kassala, including large volumes of organic waste, weak WASH and energy services, and limited livelihood options, make decentralized CBE solutions both suitable and necessary. Feasible CBE pathways include nutrient recycling, small-scale bioenergy, circular sanitation, greywater reuse, and feed production. These options can ease pressure on the environment and enhance basic services while creating income for displaced and host communities. While the analysis drew primarily on secondary data, this approach provided a rapid, system-level understanding of pressures, opportunities, and entry points across highly dynamic and insecure contexts. It offers a robust strategic foundation for action in settings where access constraints and fast-changing conditions limit the availability of up-to-date, state-level datasets. This framing enables the identification of transferable CBE principles and priority pathways that can be adapted across diverse settlement typologies. Future work will build on this foundation through targeted field engagement with communities, humanitarian actors, and local authorities to ground-truth assumptions and translate these entry points into operational models. This will include quantifying waste streams, mapping local resource flows, and assessing existing informal reuse practices. Conflict-sensitive and protection analyses will guide safe and equitable roll-out, alongside studies of costs and economic viability. Together, this evidence will enable partners to develop realistic, state-specific implementation models that define suitable technologies, governance arrangements, and training requirements

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