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Short Communication

Assessing lignocellulosic biomass as a source of emergency foods

Niroshan Siva, Charles T. Anderson *

Department of Biology, The Pennsylvania State University, University Park, PA, 16802, USA

A R T I C L E I N F O

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A B S T R A C T

Catastrophes such as a nuclear war would generate atmospheric soot and reduce sunlight, making it difficult to grow crops. Under such conditions, people might turn to inedible plant biomass for nutrition, but the convertibility and nutritional content of this biomass have not been rigorously analyzed. We found that if plant biomass were converted into food at 30% efficiency, 6.7 kg of biomass per day would yield adequate carbohydrates, but contain potentially toxic or insufficient levels of other nutrients for a family of four. Therefore, exploiting biomass with low mineral content for carbohydrates and consuming other sources of protein, fat, and vitamins such as edible insects/single-cell proteins and vitamin supplements could provide a balanced diet in a global catastrophic environment.

1. Introduction

Global catastrophes such as supervolcano eruptions and large asteroid strikes, as well as human-caused events of mass destruction such as nuclear conflicts, would create widespread firestorms on Earth (Wagman et al., 2020). These firestorms would produce soot that could remain in the upper atmosphere for over a decade, limiting sunlight and lowering global temperatures (Coupe et al., 2019; Neild et al., 1998). These environmental disruptions would prevent photosynthesis, leading to crop failures (Jägermeyr et al., 2020; Neild et al., 1998). Ashfall on plant leaves would also limit their exposure to sunlight (Neild et al., 1998). Stored foods, remaining edible crops, and surviving animals might provide sustenance for survivors of a global catastrophe for a short period, but alternative nutritional solutions would be needed for long-term survival (Denkenberger and Pearce, 2014; Pham et al., 2022).

One such alternative is the use of inedible plant biomass for human nutrition. Forests cover 31% percent of the world's land surface (FAO, 2020b) and grasslands occupy another 20–40% (FAO, 2020a). Overall, plants are estimated to embody a total global biomass of 450 Gt of carbon (Bar-On et al., 2018), roughly half of which is in the form of cellulose (Bengtsson et al., 2020). If the cellulose in this biomass were depolymerized to glucose, it could potentially fulfill the caloric requirements of the current worldwide population (8 billion) for 324 years given the caloric content of glucose (USDA, 2020a) and daily energy requirements per person (USDA, 2020b) (Supplementary Material 1). However, cellulose and other components of plant biomass, such as lignin, cannot be digested by humans due to the lack of appropriate enzymes. Thus, processing is necessary to transform lignocellulosic biomass into food.

Recovering soluble sugars from plant cell walls is challenging because these walls are composed of interacting networks of cellulose, hemicelluloses, pectins, and lignin and have undergone natural selection for recalcitrance to degradation (Holland et al., 2020). Physical treatments, such as soaking or cooking in water, chewing, or grinding can release free sugars, amino acids, fats, minerals, and vitamins from soft plant tissues that can be readily digested by humans (Parada and Aguilera, 2007; Saiga and Oikawa, 1995; Zheng et al., 2011). Human gut microbiomes can also metabolize some complex carbohydrates to short-chain fatty acids (Bhattacharya et al., 2015; Ndeh et al., 2017; Oliphant and Allen-Vercoe, 2019), but the energy produced by this metabolism is only 10% of the daily energy requirement (Bergman, 1990). Therefore, in a lignocellulose-based diet, deconstruction of complex cell wall components to convert them into simple sugars would be needed prior to consumption to obtain enough energy for survival and daily activity (Mahmood et al., 2019).

Much research has been conducted to identify effective strategies for breaking down cell walls into sugars to produce biofuels and other plant-derived products (Kumar et al., 2020; Onumaegbu et al., 2018), but these methods do not typically focus on providing nutrients for humans. A subset of these deconstruction strategies might be adapted to convert inedible plant biomass to edible foods to provide nutrition after a catastrophic event, but this possibility has not been thoroughly examined.

During industrial processing, plant biomass can be physically or

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* Corresponding author.
E-mail addresses: nxs5610@psu.edu (N. Siva), cta3@psu.edu (C.T. Anderson).

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chemically pretreated by grinding/milling, soaking, heating, or adding acid or alkali solutions to degrade and separate lignin and pectin from cellulose and hemicellulose (Carvalheiro et al., 2008; Mahmood et al., 2019). However, to release substantial amounts of sugars, these treatments must often be combined with enzymatic or biological treatments, such as addition of cellulase-containing enzyme cocktails or bacterial or fungal fermentation (Carvalheiro et al., 2008). All of these processes can be energy-consuming, costly, and resource-intensive (Roy et al., 2020). After a catastrophic event, extracting carbohydrates and other essential nutrients from plants could be particularly challenging because people might lack resources.

In this study, we analyze whether plant biomass would be sufficient to meet the basic nutritional needs of a typical family of two adults and two children under post-catastrophic conditions. We find that although caloric (from carbohydrates) requirements could be met using reasonable quantities of biomass, toxicity for certain vitamins and minerals would be a problem (depending on the biomass type). Requirements for protein, fat, and several micronutrients would need to be met using additional nutritional sources. We also make recommendations for food readiness and resilience that could be used for pre-catastrophic planning.

2. Human nutritional needs would increase under post-catastrophic conditions

For this analysis, we first obtained the Acceptable Macronutrient Distribution Range (AMDR), Recommended Dietary Allowance (RDA), and Upper Tolerable Limits (UTL) data for the people at the age of 2–50 years from (USDA, 2020b) and (National Academies of Sciences, Engineering, and Medicine, 2019) and aligned the data to define the baseline nutrient requirements for a family with two adults (between 18 and 50 years old) and two children (10 years old and 2 years old) (Supplementary Material 2). Macronutrient requirements are calculated based on the energy requirement of individuals with moderate daily activity (equivalent to walking 1.5 to 3 miles per day at 3 to 4 miles per hour, in addition to the activities of independent living) (USDA, 2020b) wherein voluntary travel is limited but abundant stocks of lignocellulosic biomass and basic tools for harvesting and transporting the biomass are available. Then, we calculated the total required nutrients for the family by adding up the individual nutrient requirements (Supplementary Material 2).

Carbohydrate intake should be 45–65% of the total energy requirement for all age groups and protein intake should be 5–20% of the total energy intake for 1–3 year old children, 10–30% for 4–18 year old children, and 10–35% for adults. Acceptable fat intake ranges from 30–40%, 25–35%, and 20–35% of total energy intake for the respective age groups, and a variety of minerals and vitamins are also required in relatively small amounts (Supplementary Material 3).

Considering post-catastrophic environmental conditions, lower ambient temperatures would necessitate increased macronutrient intake to maintain proper body function. For example, depending on activity level and the availability of shelter, heating, and appropriate clothing, a temperature reduction from 20 °C to 0 °C might require at least an additional 400 kcal/day (WHO, 2004) which accounts for an additional intake of 45–65 g of carbohydrates, 10–35 g of protein, and 9–16 g of fat (Fig. 1). Micronutrient needs for individuals might increase along with increased caloric requirements under cold temperatures due to the functions of several micronutrients in human metabolism to produce energy (Reynolds, 1996). Under cold conditions, it is suggested to increase the intake of vitamin E, thiamin, riboflavin, niacin, pantothenic acid, folic acid, vitamin B_{12}, vitamin C, magnesium, iron, and zinc (Reynolds, 1996). However, precise recommendations for intake levels of micronutrients for humans in cold environments do not yet exist due to ethical and practical research limitations.

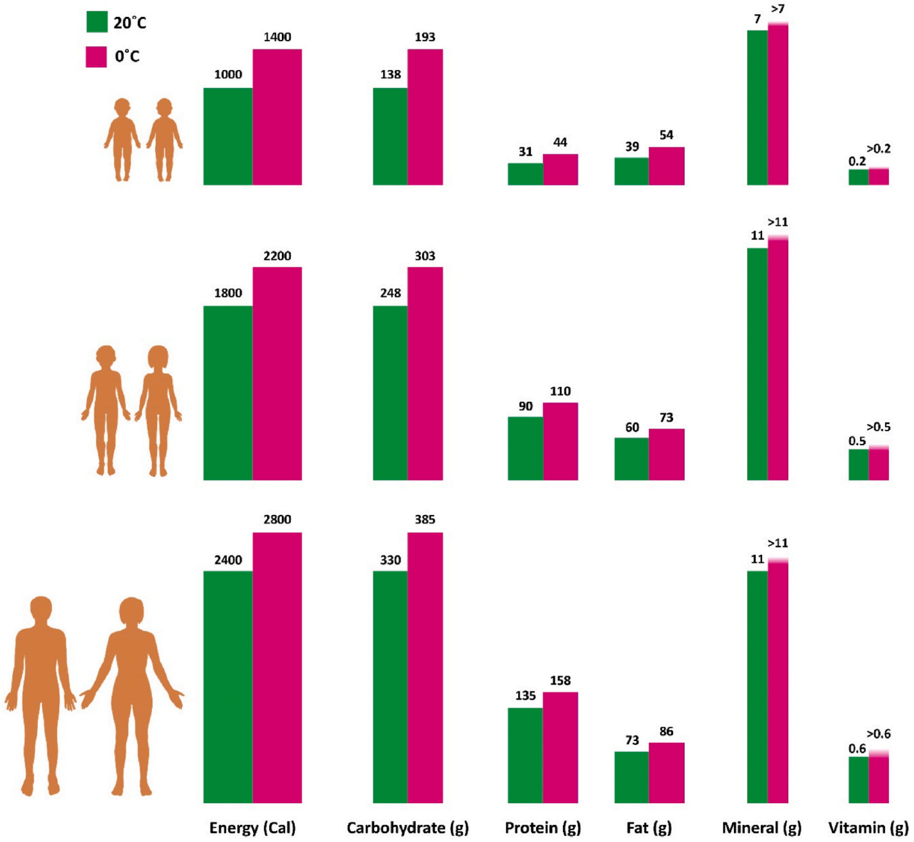

Fig. 1. Gender-averaged nutrient requirements (g/day) for 2-year-old, 10-year-old, and adult (18–50 years old) humans with moderate activity increase under low temperatures. Energy consumption should be increased by 100 kcal/day for every 5 °C reduction in the environmental temperature for proper body function (WHO, 2004) and therefore, carbohydrate, protein, and fat intake should be increased. Micronutrient requirements for individuals might increase under cold temperatures due to their functions in human metabolism to produce energy. However, there are no recommended intake levels of micronutrients for the cold environment. Scales for energy, macronutrients (carbohydrates, proteins, and fats) and micronutrients (minerals and vitamins) differ. Minerals and vitamins represent all minerals and vitamins combined but individual acceptable limits differ depending on the specific mineral and vitamin. Portions of this figure use images that are in BioRender (https://biorender.com).

3. Inedible plant biomass is generally rich in carbohydrates, vitamins, and minerals but deficient in proteins and fats depending on the type of biomass

We next sought to quantify the nutritional composition of different types of plant biomass. We categorized plant biomass into five types: leaves, forages, grasses, crop residues, and woods (Supplementary Material 4), and assumed a conservative case of 30% nutrient extraction efficiency for each type. Based on available data (Supplementary Material 4), under normal environmental temperatures (i.e., 20 °C), all biomass types contain sufficient carbohydrates (after converting to digestible sugars) to meet the daily nutritional requirement of an adult provided they consume 2.1 kg of a single type of biomass, which equals the average current mass of food intake per person per day (Fig. 2 and Supplementary Material 5). Obtaining nutrients from 2.1 kg of leaves or forages, but not other biomass types, could also provide the minimum protein daily requirement of an adult under normal environmental conditions, but any of the biomass types alone does not fulfill the protein requirement under cold conditions (i.e., 0 °C). Also, the same amount of biomass does not fulfill needs for fat and several vitamins while exceeding the upper tolerable limit of minerals depending on the biomass type (Figs. 2 and 3). This information is based on the data provided in Supplementary Material 4 and therefore the potential of biomass to meet nutrient requirements might differ depending on the actual biomass, extraction technique, human factors such as age, gender, pregnancy, and activity level as well as environmental factors such as temperature and resources in a catastrophic environment.

Different types of biomass vary in composition, and long-term nutrition derived from one type of biomass might lead to nutrient deficiency or toxicity for certain nutrients (Figs. 2 and 3). For example, considering a location where wood is abundant and other biomass types are limited and when optimizing for carbohydrates, 2.1 kg of wood would meet carbohydrate and several mineral requirements for an adult, but only 3% of protein requirements would be met and fat and multiple vitamin requirements would not be fulfilled (Figs. 2 and 3). In a location lacking wood, 1.4 kg of forage and 0.34 kg of crop residues would fulfill 100% of carbohydrate and 160% of mineral requirements, but only 37% of protein, 14% of fat, and 18% of total vitamin needs would be met (Figs. 2 and 3). Therefore, separating nutrients from several types of biomass and mixing them in appropriate ratios to develop nutrient-balanced foods, or exploiting biomass only for carbohydrates and also consuming other foods such as insects (6–66% protein and 2–62% fat on a dry weight basis) (Varelas and Langton, 2017) or single-cell proteins (39–65% protein on a dry weight basis) (Spalvins et al., 2018) along with mineral and vitamin supplements, could meet the nutritional needs of a family.

4. Large stockpiles of biomass would be required by a family to meet its nutritional needs for the duration of a post-catastrophic winter

Previous work has predicted that a nuclear winter following a global nuclear conflict would last at least 10 years (Coupe et al., 2019). Based on the nutritional needs of the individuals in the family, Table 1 shows the biomass requirement per day at 100% (ideal) or 30% (conservative) nutrient extraction efficiencies (Supplementary Material 6). Assuming ideal extraction efficiency, 6.2 kg of biomass per day would fulfill the nutritional requirements of a family, with fat being the limiting factor. Under the conservative extraction assumption, which is likely more realistic, 20.6 kg of biomass would be required per day (with the assumptions that fat and certain vitamin sources would not be directly available from biomass). For the conservative case, this translates into 75190 kg of biomass required to feed a family of four per year (Supplementary Material 7) and therefore, the current global forest biomass could be used to feed ~6 billion families (24 billion people) for 10 years using a forest area of 0.7 ha (7000 m^2) per family. However, considering only caloric requirements and assuming that calories come only from carbohydrates, forest biomass could be used to feed 10–30 billion families for 10 years or 2 billion families for 50–150 years with a required forest area per family of 0.13 ha (1300 m^2) for the ideal case and 0.41 ha (4100 m^2) for the conservative case.

5. Discussion

Here we analyzed the post-catastrophic nutritional needs of a typical family of four and calculated the amounts of plant biomass that would

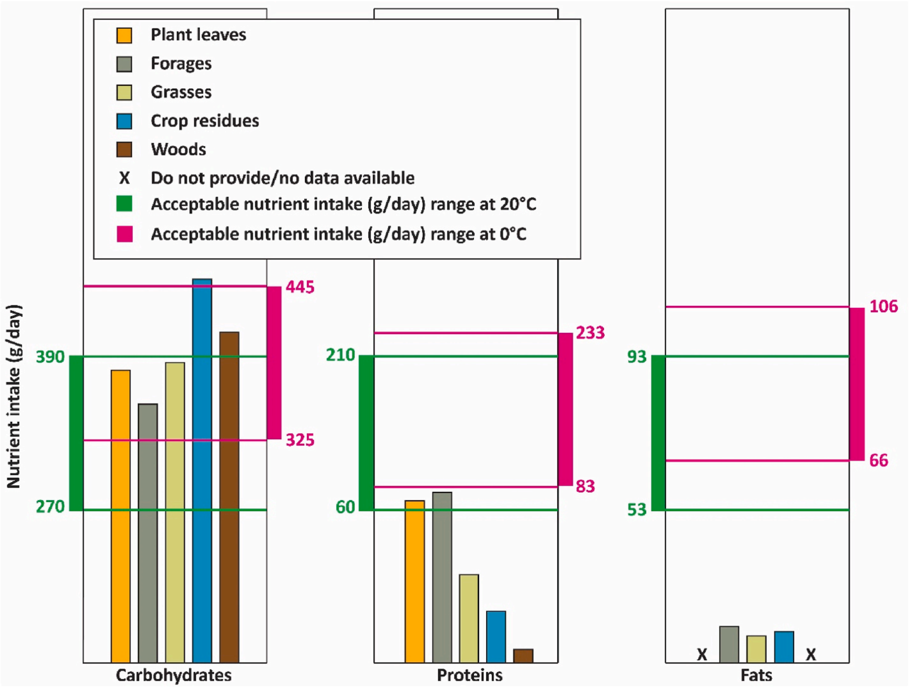

Fig. 2. Potential of different types of plant biomass to provide macronutrients (g/day) under post-catastrophic conditions. Regions bounded by green lines show acceptable nutrient distribution ranges for a moderately active adult (18–50 years old) living in a 20 °C environment with a daily food intake of 2.1 kg of biomass (at 30% nutrient extraction efficiency). Magenta lines show the nutrient requirements if the ambient temperature decreases to 0 °C. Reducing the environmental temperature demands more energy, hence more nutrients to sustain activity.

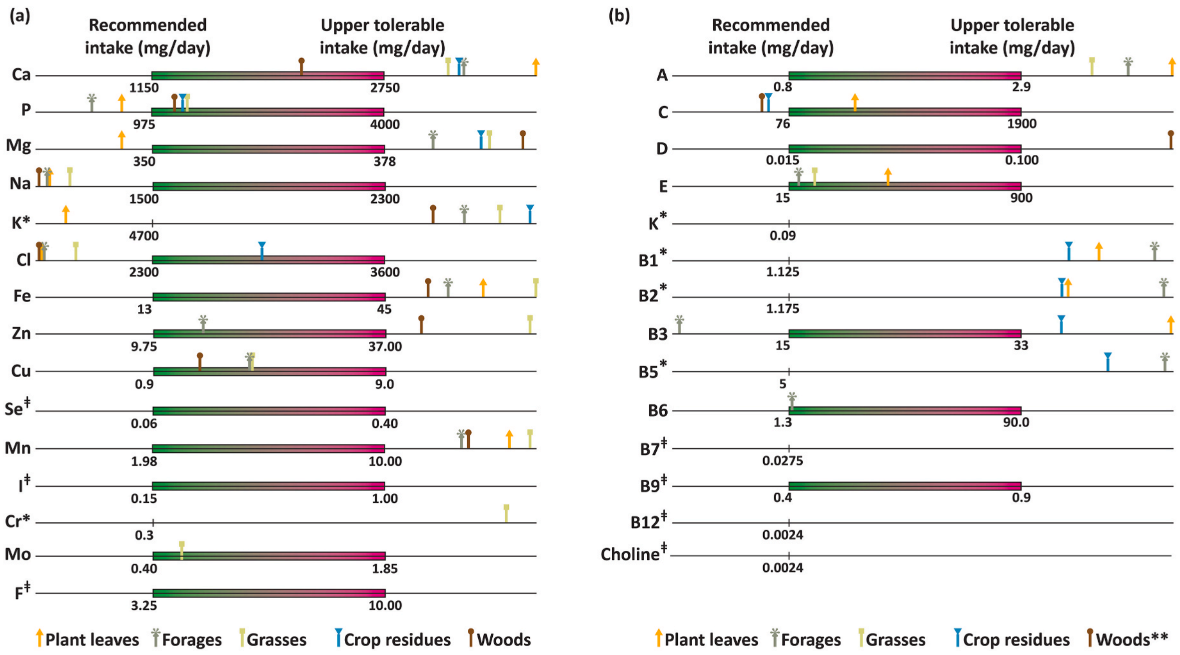

Fig. 3. Potential of different types of plant biomass to provide minerals (a) and vitamins (b) under post-catastrophic conditions. Regions indicated by green to magenta shaded bar show acceptable nutrient distribution ranges for an adult (18–50 years old) living in a 20 °C environment with a daily food intake of 2.1 kg of biomass (at 30% nutrient extraction efficiency). Data for mineral and vitamin requirements at low temperatures (i.e., 0 °C) are not available but the requirements might be higher in colder temperatures due to their involvement in human metabolic activities (Reynolds, 1996). Scales for acceptable range, below recommended intake, and upper tolerable intake differ. *Several minerals and vitamins do not have upper tolerable limits due to no toxicity or lack of data. ‡There are no available data for minerals and vitamins for the biomass types provided in Supplementary Material 4. **Vitamin D content of wild tree-grown mushrooms is used as a proxy for the vitamin D content of wood.

Table 1

Amount of plant biomass required to obtain adequate nutrients for a family of two adults between 18 and 50 years old and two children (10 years old and 2 years old) under a post-catastrophe condition*.

Nutrients	Preferred biomass type	Amount of biomass (kg)**	
		Ideal case	Conservative case
Carbohydrates	Plant leaves, forages, grasses, crop residues, and woods	2.0	6.7
Protein	Plant leaves, forages, grasses, and crop residues	6.2	20.6
Fat	Forage, grasses, and crop residues	17.6	58.6
Minerals	Plant leaves, forage, grasses, crop residues, and woods	1.6	5.5
Vitamins	Plant leaves	1.1	3.7

* Post-catastrophic environmental temperature is considered as 0 °C.

** The amount of biomass is calculated for two scenarios: ideal condition (100% extraction efficiency of biomass) and conservative condition (30% extraction efficiency of biomass).

be required to meet those needs. We determined how much plant biomass would be required to meet the nutritional needs of a family of two adults and two children and described appropriate adjustments for nutritional requirements under post-catastrophic conditions (i.e., low environment temperature). Depending on the type of biomass and the conversion technique, the amount of nutrients that could be obtained varies substantially (Supplementary Material 4 and 8).

Our analysis shows that several biomass types can meet the carbohydrate, mineral, and multiple vitamin requirements of a family, but the protein and fat requirements would not generally be met under post-catastrophic conditions (Figs. 2 and 3). Therefore, alternative food sources such as single-cell foods (for protein), edible insects (for protein and fat), and supplements (for several minerals and vitamins) would be needed. Certain edible fungi such as *Polyporus tenuiculus* and *Neurospora intermedia* can be grown on lignocellulosic biomass and agricultural wastes, although additional nitrogen might be required to produce sufficient protein (Andayani et al., 2020; Karimi et al., 2019; Omarini et al., 2009). Several edible insects such as *Arhopalus rusticus* (wood--boring beetle), *Nasutitermes jaraguae* (termite), and *Hermetia illucens* (Black Soldier Fly) can use biomass as an energy source and provide essential nutrients for humans (Varelas, 2019). For example, *H. illucens* larvae grown on agricultural waste contain 40–47% protein and 24–32% fat, requiring only 0.9–1.0 kg and 0.8–1.4 kg of insect biomass (dry weight) to meet the protein and fat needs of a family per day, respectively (Ramzy et al., 2022).

Resources for the conversion of biomass to food will vary depending on the size and the nature of the catastrophe. Fig. 4 shows potential food conversion methods that would require moderate to high resources such as electricity, access to drinking water, and less damaged infrastructure. At a household level, people might have basic methods to preprocess biomass such as cutting the wood into small pieces and grinding them to reduce the particle size. Preprocessed biomass can be used to grow edible mushrooms or insects and grow single cell species (yeast or green algae) after converting lignocellulosic biomass into sugars or acetate via digestion and/or fermentation (Hann et al., 2022; Sun et al., 2021). Raw biomass or the residual biomass after mushroom cultivation can be used to grow small ruminants or pseudo-ruminants such as rabbits (Meyer et al., 2021; Spinosa et al., 2008). Further, household-level greenhouses could be maintained to grow vegetables and microgreens using artificial lights and room heaters (Appolloni et al., 2022). The grown and converted foods might require additional processing such as boiling before consumption to increase the digestibility and reduce toxicity (Becker, 2007; Hadi and Brightwell, 2021). For example, solanine, a compound that can cause diarrhea, abdominal pain, dizziness, and numbness, can be removed from potato leaves by dipping in vinegar (0.3–1.0% acetic acid) at 30–60 °C for 2–5 min (Lee Byung-cheol, 1999). Further, these foods might be canned or dried for long-term storage.

Catastrophic events would create an unfavorable environment for

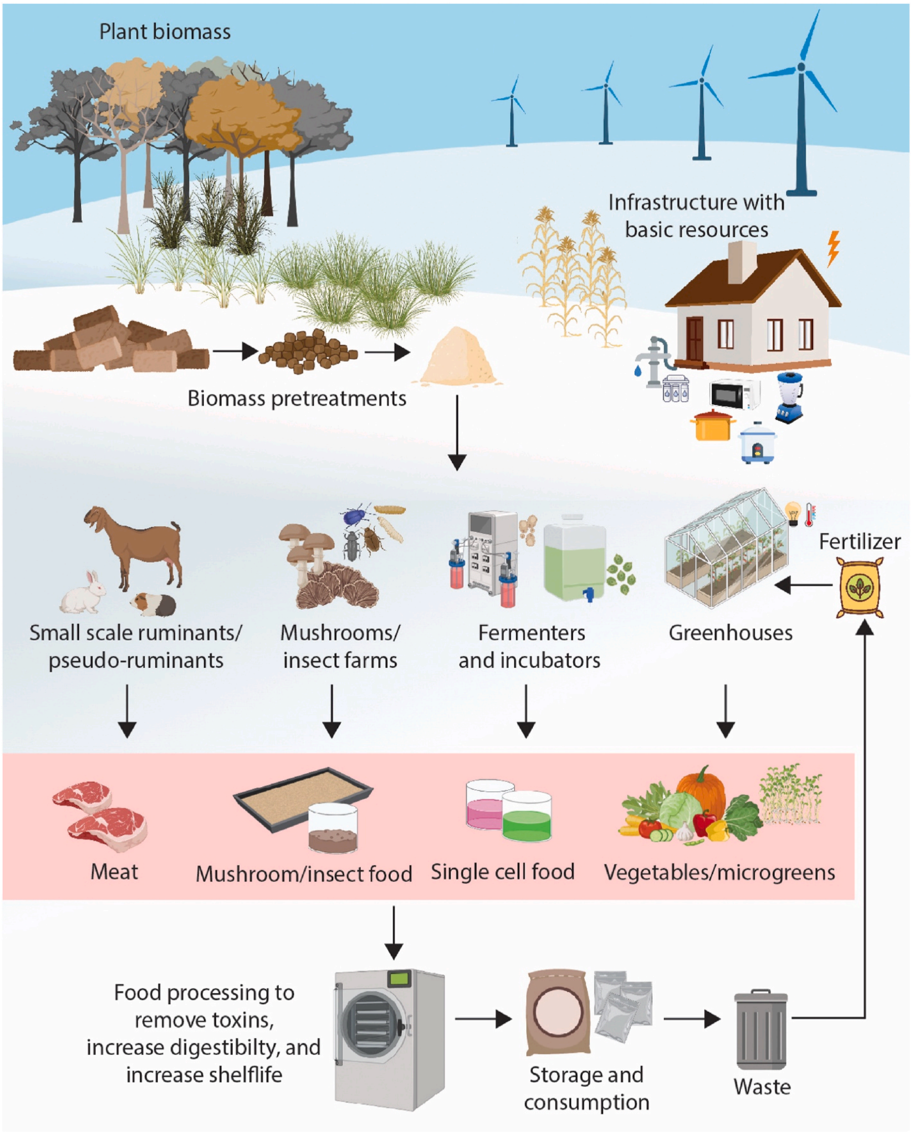

Fig. 4. Resources needed to convert biomass into edible foods in a moderately affected area after a catastrophe. Four stages are identified for effective conversion techniques and storage of foods. First stage: acquiring biomass and preprocessing; second stage: converting the biomass into foods in several methods (mushroom products, single cell foods, vegetables/microgreens, and small-scale ruminants/ pseudo ruminants); third stage: food processing to remove toxins, increase digestibility, and increase shelflife; fourth stage: consuming nutritionally balanced converted food by mixing several types of foods, storing foods for future consumption, and waste management via recycling. Portions of this figure use images that are available for non-commercial use in Google and BioRender (https://biorender.com/).

agricultural activities. We recommend growing nutrient-rich edible plants around households at present (e.g., fruit trees) to use as foods during a catastrophe and maintaining emergency grain stockpiles, protein bars, oils, canned and dried food products, and mineral and vitamin supplements to fulfill immediate food needs. Growing frost-resistant crops such as winter wheat (*Triticum aestivum*) (Wilson et al., 2023) and scaling greenhouses to grow crops in low light (Alvarado et al., 2020) might be possible, but they alone would not be enough to feed large populations. For longer-term needs, people might depend on leftover crop residues, tree leaves, grasses, woods, and biomass-derived insect/single-cell food farming to get nutrients to survive. At present, there are limited efficient, cost-effective extraction methods to convert biomass into edible foods, especially after a catastrophic event. Therefore, new extraction techniques and process optimization are needed to increase the conversion efficiency of inedible plant biomass to edible food. Further, an inventory of potentially toxic components of plant biomass and toxin removal methods prior to consumption is needed (Mottaghi et al., 2023; Pearce et al., 2019).

CRediT authorship contribution statement

Niroshan Siva: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Charles T. Anderson:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: none.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crfs.2023.100586.

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