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Synthetic fat from petroleum as a resilient food for global catastrophes: Preliminary techno-economic assessment and technology roadmap

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ABSTRACT

Human civilization's food production system is unprepared for global catastrophic risks (GCRs). catastrophes capable of abruptly transforming global climate such as supervolcanic eruption, asteroid/comet impact or nuclear winter, which could completely collapse the agricultural system. Responding by producing resilient foods requiring little to no sunlight is more cost effective than increasing food stockpiles, given the long duration of these scenarios (6–10 years).

This preliminary techno-economic assessment uncovers significant potential for synthetic fat from petroleum as a resilient food source in the case of an abrupt sunlight reduction catastrophe, the most severe food shock scenario. To this end, the following are roughly quantified based on literature data: global production potential, capital and operating expenditures, material and energy requirements, ramp-up rates and retail prices. Potential resource bottlenecks are reviewed.

Synthetic fat production capacity would be slower to ramp up compared to low-tech food production alternatives, but provides the fat macronutrient, largely absent from these. Using 24/7 construction of facilities, 16–100% of global fat requirements could be fulfilled at the end of the first year, potentially taking up to 2 years to fully meet the requirements. Significant uncertainty remains on several topics including production potential, capital expenditure, food safety, transferability of labor and equipment construction. A technology roadmap is proposed to address these concerns and develop the potential of synthetic fat as a catastrophe-resilient food.

1. Introduction

1.1. *Resilient foods for GCRs*

The most extreme food catastrophes possible that have been identified in literature fit under the classification of *abrupt sunlight reduction scenarios*. In these, a catastrophic event causes an abrupt large emission of aerosol material such as sulfates, soot and black carbon to be projected to the atmosphere and remain there for a period of multiple years. This would cause a catastrophic descent of the amount of sunlight incident over the surface of the Earth, global temperatures and precipitation levels, resulting in near-complete collapse of conventional agriculture. At

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Abbreviations: CAPEX, capital expenditure; CEPCI, Chemical Engineering Plant Cost Index; FEED, front-end engineering design; FEL, front-end loading; GCR, global catastrophic risk; GTL, gas-to-liquids; NPV, net present value; OPEX, operational expenditure; RM, *Reichsmark*; SFA, synthetic fatty acid; tpa, tonnes per year; USM, unsaponifiable matter; WHO, World Health Organization.

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least three mechanisms for such a catastrophe have been identified in literature, namely: a supervolcanic eruption causing a global volcanic winter, the impact of a very large asteroid or comet, and a nuclear winter caused by multiple nuclear detonations over flammable material (Bostrom and Cirkovic, 2008; Denkenberger and Pearce, 2015). These scenarios can be categorized as Global catastrophic risks (GCRs), events that threaten the well-being of humanity and potentially the existence of civilization itself (Turchin and Denkenberger, 2018).

One model of such a scenario (nuclear winter) estimates a reduction of ∼50% of solar irradiation for 6–10 years, causing a ∼10 °C maximum global temperature drop (Robock et al., 2007; Coupe et al., 2019). Some researchers have estimated the likelihood of an inadvertent nuclear war taking place to be as high as ∼1%/year (Barrett et al., 2013). This type of GCR would prevent any crops from growing outdoors that are not cool-tolerant. Furthermore, the growing season would be very short outside of the tropical latitudes, allowing very few crops to grow there. A severe global food catastrophe would cause an abrupt disruption in food production causing potentially billions of people to starve, with little opportunity for adaptation absent previous preparation. A separate class of catastrophes would affect food indirectly by disrupting electricity/industry, and then different solutions are required (Abdelkhaliq et al., 2016; Cole et al., 2016; Denkenberger et al., 2017).

Resilient food production methods are needed for scenarios that do not allow conventional agriculture. The most apparent alternatives to conventional agriculture in an abrupt sunlight reduction scenario include artificial light grown crops and food storage. Artificial light photosynthesis is high cost and requires high energy demand for many reasons, predominantly due to the use of precise environmental control (Alvarado et al., 2020). Producing artificial light grown crops during a GCR would add a cost to current food of roughly $600/dry kg (Denkenberger et al., 2019) and could feed only around ∼5% of the global population by using all of the current global electricity demand (Denkenberger and Pearce, 2014). Storing sufficient food ahead of time would be very expensive and considerably reduce food availability during the storage period (Denkenberger et al., 2019).

Resilient food solutions are needed to deploy food quickly, cost effectively, and energy efficiently to feed the global population. Resources of industries not used for the production of food could be recycled or diverted toward repurposing existing factories such as pulp and paper for food production (Throup et al., 2021) or building resilient food production plants. This would be economically justified if the demand for that food product is high enough. Promising resilient food solutions include relocating cool-tolerant crops, cultivating crops in low-tech greenhouses (Alvarado et al., 2020), scaling up global seaweed production (Mill et al., 2019), leaf protein extract (Pearce et al., 2019), mushrooms, cellulosic sugar (Throup et al., 2021), insects, ruminants (Denkenberger and Pearce, 2015), protein from hydrogen-oxidizing bacteria (García Martínez et al., 2021c) or methane-oxidizing bacteria (García Martínez et al., 2020) and acetic acid from microbial electrosynthesis (García Martínez et al., 2021b). Effective resilient foods are inexpensive to prepare for in comparison to solutions such as artificial light and global-scale food storage, and investment in these could save expected lives cost effectively (Denkenberger and Pearce, 2016, 2018). To the best of our knowledge, neither the United Nations nor any particular government has a publicly available response plan to an abrupt sunlight reduction scenario as described here. Currently few organizations are working on resilient food solutions for abrupt sunlight reduction, including the *Alliance to Feed the Earth in Disasters* (ALLFED, 2020), *Pennsylvania State University* in collaboration with *Open Philanthropy* (LaJeunesse, 2020), and the *Centre for the study of existential risk* (Tzachor et al., 2021).

1.2. *Aims and scope*

In the case of a sunlight reduction catastrophe, fat sources would likely become scarce. Few of the resilient foods for catastrophes proposed so far are rich in fat. Key sources could include wild-caught seafood (Scherrer et al., 2020) and farmed animals. For example, some milk, meat, offal and bone meal from ruminants or meat from insects, both being fed with agricultural residues, partially digested biomass (Denkenberger and Pearce, 2015) or grass, if available. Another prominent option, if feasible, would be the cultivation of fat-rich crops in greenhouses in the tropics (Alvarado et al., 2020). For this reason, alternative sources of fat would be greatly advantageous for contributing to the fulfillment of the fat requirements of the population and introducing diet diversity and redundancy in fat production during the catastrophe. Non-biological synthesis of fat from readily available resources such as fossil fuels could be one such alternative, since it does not require sunlight, and has been done in the past. This study aims at a preliminary analysis of its potential as resilient food with a scope akin to a FEL-1 stage (front-end loading) in which the concept is defined and preliminary diagrams and budget estimates are produced, but the level of detail is not yet sufficient for construction (Warner, 2019).

More generally, the aim of this work is contributing to GCR preparedness and planning for possible future GCR response efforts. In this way, the findings could also reduce existential risk via reduction of existential risk factors. Existential risks relate to events with the capacity to eliminate humanity or its future potential (i.e. by preventing civilizational recovery) (Bostrom, 2013), while risk factors weaken our defenses to these events (Cotton-Barratt et al., 2020). Examples of the latter could be social turmoil or bad global governance during a global catastrophe unleashing the potential of an event to become an existential catastrophe. In addition to prevention, response and resilience have been proposed as fundamental defense layers against existential risk (Cotton-Barratt et al., 2020).

1.3. *Historical context*

This work is inspired by the historic precedent found in World War 2 Germany. In 1939, during a fat shortage, a non-biological process was developed to convert byproducts of the conversion from coal to liquid fuels into edible fat for human consumption. This byproduct, known as "*gatsch*" or paraffin wax, is a waxy fraction of the Fischer–Tropsch liquid product containing mostly alkane compounds, also known as paraffinic hydrocarbons or paraffins. These can be subjected to a chemical reaction known as paraffin oxidation, causing the rupture of the alkanes into "synthetic" fatty acids (SFAs). Most of these SFAs were dedicated to soap production, but a part was processed into human food. These were subjected to purification and esterification with glycerol to produce triglycerides that could be refined into a synthetic margarine-like product. This was known as *butter aus kohle* or "coal butter" (BIOS, 1946; Asinger, 1968; Frankenfeld, 1968).

In normal conditions, fats of agrichemical origin are more economical to produce than SFAs due to the capital intensity of the latter. However, during the shortage conditions in WW2 Germany the "coal butter" was allegedly cheaper to produce than regular butter (Eagle Valley Enterprise, 1946), presumably due to the very high price of butter in Germany at the time. Pricing data from 1939 indicate the large retailer price of margarine at 1.74 *ReichsMark* (RM) per kilogram (Statistichen Reichsamt, 1939), which would be approximately equivalent to 13 USD in 2020.

Production of edible synthetic fat was discontinued completely during the 1950s, but SFA production continued to develop. In 1959 the USSR decided to replace 40% of the natural fatty acids used for soap production via SFA synthesis (Zilch, 1968). In 1978, over 500,000 t of SFAs were obtained via continuous paraffin oxidation processes in Eastern Europe (Fineberg, 1979). However, SFA production eventually fell out of use due to the lower cost and higher quality of agrichemical fatty acids, and has not been economical for several decades (Anneken et al., 2006).

1.4. *Nutrition and safety of synthetic fat*

The nutritional value of the German "coal butter" has historically been called into question. The German fat contained around 50% of odd chain fatty acids, rarely found in vegetable or animal fats, which was raised as a concern. The small proportion of iso and branched chain fatty acids contained in the product was also considered concerning due to their potential toxicity. In addition, the product could contain non-negligible amounts of toxic compounds such as hydroxy, keto and dicarboxylic acids as well as alcohols and ketones (Frankenfeld, 1968).

Animal trials showed that the presence of branched fatty acids reduced the digestibility of the synthetic fat. The synthetic fat performed worse than natural fat in weight gain tests, and synthetic fat based on pure branched fatty acids produced no weight gain (BIOS, 1946). Human trials indicated that the iso fatty acids present in the synthetic fat could cause excessive presence of dibasic acids in urine, which can lead to kidney and bone decalcification disorders (BIOS, 1946; Meyer-Döring, 1949). On the other hand, the presence of odd chain fatty acids was not found to have negative physiological effects (Meyer-Döring, 1949); it is now well known that they are safe to eat and even potentially beneficial (Venn-Watson et al., 2020). Regarding the presence of hydroxy, keto and dicarboxylic acids, alcohols and ketones, it was claimed that judicious selection of catalysts and operating parameters could remove most of these unwanted compounds (Frankenfeld, 1968).

Values on the safe usage of the synthetic fat vary wildly. Some researchers claim humans can tolerate only up to 10–20 g per day (Frankenfeld, 1968), while others claim that it was used in amounts as high as 100 g per day with no adverse effects (Maier, 2016). This could be related to the considerable variability in the quality of the fat (Frankenfeld, 1968), which was to be expected since the product was obtained via a batch process, sometimes using different raw materials of varied origins and properties (BIOS, 1946).

Over a thousand animal trials were performed to prove the fat was neither toxic nor irritant and could be successfully digested. Later, experiments were performed on 6000 human subjects over three years, which showed the product to be a satisfactory substitute for natural fat (BIOS, 1946). There are reports of people allegedly consuming the synthetic fat in considerable amounts for over a year with no ill effects (Frankenfeld, 1968). The synthetic fat was used by the German soldiers fighting in the African campaign and on submarines. It was also used in heavy labor rations, food for prisoners of war and concentration camp inmates and in canteen meals in hospitals (Reith and Pelzer-Reith, 2002). The taste and calorific value were reportedly similar to those of butter (DER SPIEGEL, 1947).

2. Methods

2.1. Methodology overview

The potential of a resilient food for GCRs can be characterized by the following two metrics: production ramp-up speed and retail price per calorie. The first one defines how fast the production can scale up over time, while the second one defines the affordability of the product. Another key consideration is whether the global production of the input resources is large enough, so that it would not be a bottleneck during production ramp-up. Fig. 1 presents the methodology used to arrive at these results, which is summarized below and described in depth in the following sections.

First, the reasons why paraffin wax from petroleum is chosen as a feedstock for the process (rather than coal wax as historically done) are given, namely higher global availability and lower capital intensity. Second, the relevant aspects of the chemical production process as conceptualized here are described based on historical technical literature. Then, the methodology used to perform the mass balance analysis is described, which is based on published empirical values of process performance. From these, the required material inputs are back-calculated for the desired target factory size (100,000 tpa). By comparing these to the estimated minimum food requirements of the global population, the availability of the required raw materials is reviewed to anticipate potential production bottlenecks.

The total operational expenditure is obtained by adding these raw materials costs to the cost of required utilities (based on historical values), and to the other operational costs such as maintenance, labor, laboratory costs and overheads, estimated using standard textbook values as a reference. Next, the capital expenditure (CAPEX) is estimated from a published historical source by applying a standard expression for cost-capacity estimation. The construction time is estimated from the CAPEX based on a reference class forecasting correlation, from which the production ramp-up speed is obtained by using the global chemical industry budget as a proxy of the amount of available resources for plant construction. Finally, synthetic fat production and retail unit costs are obtained from an NPV economic analysis based on typical financial assumptions.

2.2. Raw material selection

In general, for a resilient food to be able to make a significant contribution to the global food requirements, the following characteristics are desired for its inputs: 1) they are independent of incident sunlight, and 2) they are available in nature in very large amounts, or 3) they can be obtained in significant quantities by leveraging existing infrastructure with minimal additional processing. It is based on 1) that we decided to study the potential of synthetic fat production technology. Based on criteria 2) and 3), representative sources of the main raw materials for synthetic fat production (paraffin wax and glycerol) are reviewed in this section.

Paraffin wax is the main feedstock required for the production of edible fat via paraffin oxidation. It is an organic mixture composed mainly of straight chain saturated hydrocarbons (n-alkanes) of carbon chain length ranging from C_{18} to C_{36} (Rehan et al., 2016). It can be obtained 1) directly from the fractional distillation of paraffin-containing crude oils, or synthesized as a product of 2) coal liquefaction (e.g. Fischer–Tropsch process) or 3) low temperature hydrogenation of coal tar (BIOS, 1946; Asinger, 1968). Preferably the wax feedstock will contain mainly alkanes of carbon chain length C_{18} to C_{30}, corresponding to a molecular weight of 250–420 (Asinger, 1968). Petroleum wax consists mostly of normal n-alkanes (80–90%), the rest being branched alkanes (iso-alkanes) and monocyclic alkanes (cycloalkanes) (Rehan et al., 2016). In comparison, synthetic waxes contain few cycloalkanes (Shafer et al., 2019), but the content of branched alkanes is similar, with around 15–20% for medium pressure Fischer–Tropsch wax and 10–15% for low temperature hydrogenation wax (Asinger, 1968).

Petroleum waxes can require additional purification prior to undergoing oxidation in comparison to synthetic coal waxes. A high oil content is detrimental to the suitability of the wax for oxidation, which makes it necessary to treat the petroleum waxes with organic solvents to remove cyclic compounds such as cycloalkanes and aromatics via liquid–liquid extraction. In addition, they can contain oxidation inhibiting components such as sulphur and nitrogen compounds or phenols which delay the reaction, with a recommended sulfur and phenol content lower than 0.5%. The possible presence of cyclic and unsaturated hydrocarbons can also produce oxidation inhibiting compounds mid-reaction. Waxes that do not satisfy the technical requirements must be subject to a purification pretreatment, determined by the origin and properties of the wax, making it impossible to generalize (Asinger, 1968).

In general, petroleum waxes are a poorer starting material, but they have the clear advantage of being readily available

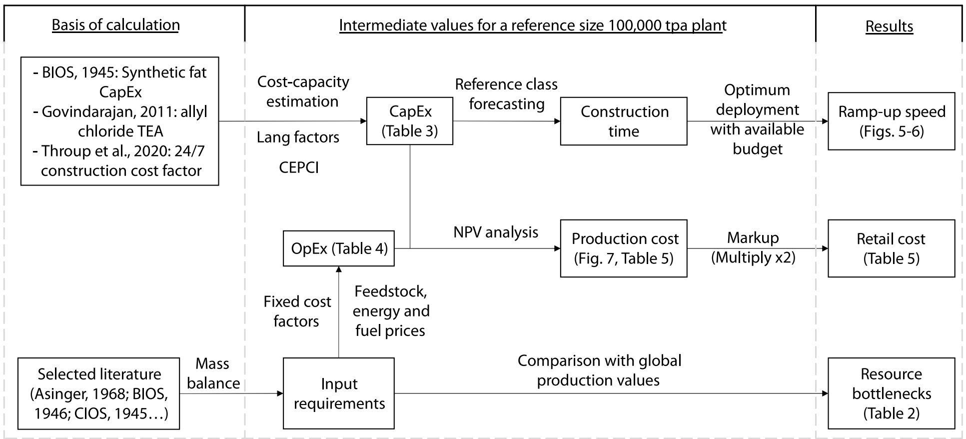

Fig. 1 – Methodology flowchart (TEA: techno-economic assessment, CAPEX: capital expenditure, OPEX: operational expenditure, NPV: net present value, CEPCI: Chemical Engineering Plant Cost Index).

in significant amounts without requiring capital intensive coal gasification and gas-to-liquids (GTL) conversion systems. Optimizing the use of resources (e.g. construction materials, equipment, human labor) in a sunlight reduction catastrophe is key so as to not be limited by them in terms of how much food can be produced. During the sunlight reduction catastrophe period lasting multiple years, it is likely more resource efficient in the short run to build petroleum wax pretreatment equipment rather than invest in costly GTL chemical plants (see Section 3.2 for the large difference in capital expenditure). Thus, petroleum wax is selected as the wax feedstock of choice.

The other feedstock required for the production of synthetic edible fat is glycerol to esterify the SFAs into triglycerides. Mentions of direct usage of the purified SFAs as cooking oil have been found (BIOS, 1945) but this option was not considered due to most mentions of the usage of synthetic fat referring to the triglyceride or “butter” form instead.

Glycerol can be obtained industrially via synthesis from propylene, oil hydrolysis, fermentation and fatty acid or oil transesterification (Bagnato et al., 2017). Today most of the global production of glycerol originates as a byproduct of biofuel production via transesterification of vegetable oil, with synthetic glycerol hardly being able to compete economically. In a sunlight reduction catastrophe, however, these production processes would be severely limited by the availability of raw materials, except for synthetic glycerol from propylene. Another non-biological route to producing glycerol which could work independently of sunlight has been proposed in literature using CO_2 as a feedstock (García Martínez et al., 2021a), but is not considered here due to insufficient technology readiness. For this reason, synthetic glycerol production via propylene chlorination is selected as the glycerol source. The overall process is thus entirely non-biological.

2.3. *Process description*

The relevant unit operations and mass flows involved in the wax to edible fat process can be found in Figs. 2 and 3. Water treatment, heat exchange and pumping are not shown. The wax feedstock may be subject to a purification pretreatment prior to this process. First, the wax is mixed with the oxidation catalyst ($KMnO_4$) and unsaponifiable matter (USM) recycled from further downstream, while stirring under heating. USM refers to material that has been partially oxidized but not yet converted into fatty acids, separated from the SFAs. The proportion of fresh wax in the reactor feed is 30–40%, the rest being recycled USM (Asinger, 1968; BIOS, 1946; CIOS, 1945).

The hot mixture is sent to the paraffin oxidation reactor, where it is treated with air as the oxidizing agent. The reaction takes place at a temperature of 105–120 °C, which accelerates the rate while limiting the production of over-oxidized byproducts (Asinger, 1968). It is exothermic, requiring continuous heat removal for temperature control. The process is carried out until 30–35% of the alkanes in the reactor feed have been converted to prevent excess over-oxidation (Frankenfeld, 1968). Traditionally the paraffin oxidation process was performed batchwise, but the use of several reactors allows for continuous processing (Asinger, 1968; Freund et al., 1982), which has been performed industrially (Zilch, 1968; Freund et al., 1982).

A simplified stoichiometry of the main chemical reaction of paraffin oxidation is derived, which is shown in Eq. (1). It is meant only as an approximate description, in which an alkane/paraffin molecule combines with oxygen to produce two fatty acids and water. R represents an aliphatic chain whose exact number of carbon and hydrogen atoms depend on the oxidation site. The combined carbon chain length of the two acids formed adds up to n. Side reactions are not shown, but are accounted for via reaction yields. The expanded reaction route and mechanism can be found elsewhere (Asinger, 1968).

$$C_nH_{2n+2} + 5/2\,O_2 \rightarrow 2\,R-COOH + H_2O \tag{1}$$

The two fatty acids thus formed will have a carbon chain length ranging from the lowest to the highest possible value that can be expected from the alkane chain rupture, between C_1 and $C_{(n\text{-}1)}$, in similar molar proportions. However, a slightly higher share of shorter chain fatty acids than statistically expected is found in practice due to longer chain fatty acids preferentially undergoing further oxidation. A roughly equal amount of even and odd carbon chain acids is produced (Asinger, 1968). An approximate carbon balance would be 20–25% of short fatty acids between C1-C9, 55–60% of larger fatty acids, around 10% carbon dioxide and monoxide (Mannes, 1944), and the rest would be composed of other byproducts.

The oxidation product is subject to a water wash with stirring and heating to remove light fatty acids, the catalyst, dicarboxylic acids and highly over-oxidized substances. The fatty acids contained in the mixture are then saponified by

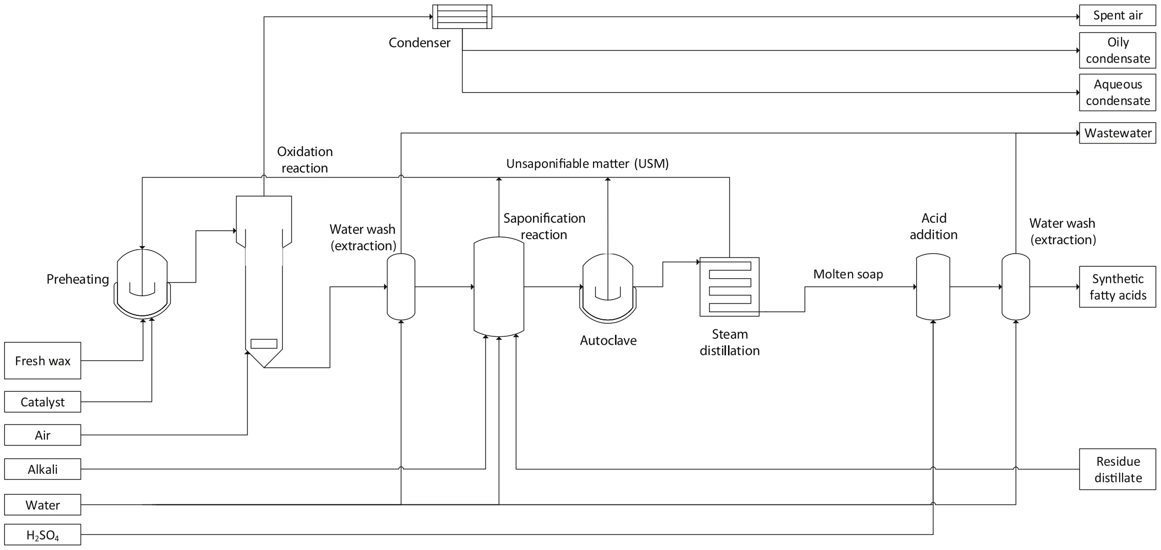

Fig. 2 – Simplified process flow diagram of the SFA production process via paraffin oxidation and saponification.

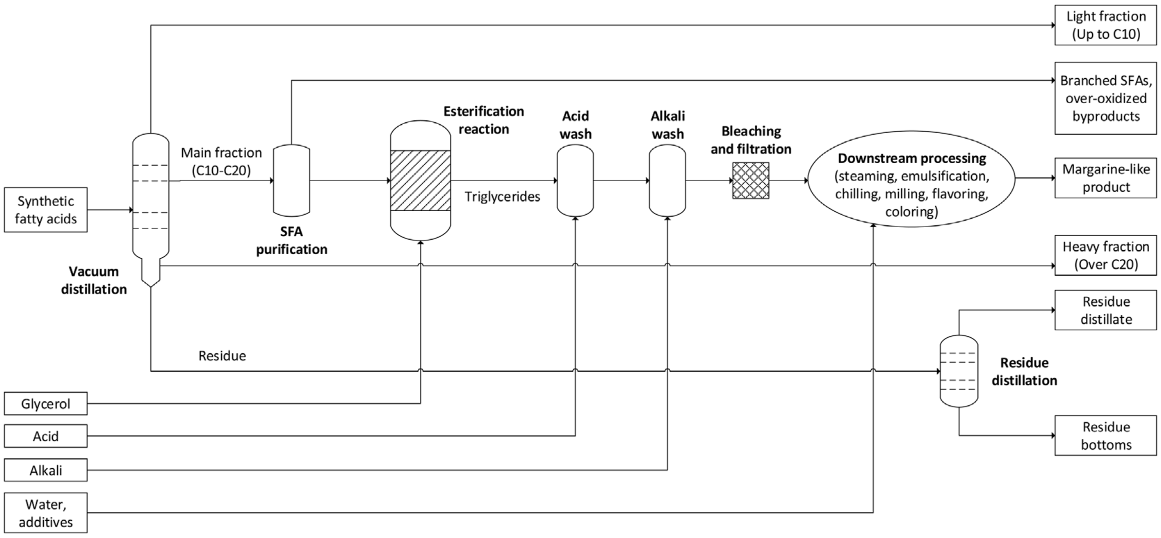

Fig. 3 – Simplified process flow diagram of the synthetic fat production via fractional separation of the SFAs and esterification with glycerol.

addition of sodium hydroxide or sodium carbonate according to Eq. (2). This is performed under heating and pressure as a separation technique, with the additional effect of cleaving ester compounds. The USM, mostly consisting of unreacted wax, is separated in three stages. First, a USM layer (USM 1) spontaneously separates from the soap phase in the saponification reactor (CIOS, 1945). Then, the mixture is subjected to heating and vigorous stirring, causing separation of part of the USM (USM 2), which is also recycled. Finally, the resulting mixture is subjected to superheated steam distillation through a high-pressure tubular system at 380 °C and high pressure. This has the double effect of breaking down part of the unwanted byproducts (lactones, esters, estolides, hydroxyacids, etc.) into unsaturated fatty acids and separating most of the remaining USM with the steam (USM 3), to be condensed and recycled. The resulting molten soap mixture consists mostly of sodium salts of C4-C22 fatty acids, which is converted back to acids via mineral acid addition (e.g. sulfuric). The acid layer is then water washed to neutralize and remove the lower water soluble acids (~10–14% of the total) (Asinger, 1968).

$$R-COOH+NaOH\rightarrow R-COONa+H_2O \tag{2}$$

Table 1 – Expected yield ranges for fatty acids of different carbon chain lengths produced via fractional distillation of the SFA product of paraffin oxidation, based on the composition of the distilled mixture (CIOS, 1945; Asinger, 1968).

Fraction	Carbon chain length	Yield (%)
Light fatty acid	Up to C10	12–20
Target fatty acids	C10–C20	55–63
Heavy fatty acids	C20–C25	7–12
Residue (over-oxidized byproducts, USM)	–	7–20

The resulting mixture is formed primarily by fatty acids, containing also some over-oxidized byproducts such as hydroxyacids, ketoacids and dicarboxylic acids. Fractional vacuum distillation is then performed, which confines most of these unwanted byproducts to the distillation residue, together with most of the USM left over. Three distinct SFA product fractions are obtained, as shown in Table 1. Historically, the SFA yield from wax was about 80% (CIOS, 1945; Eagle Valley Enterprise, 1946; Asinger, 1968).

The main SFA fraction may then need to be subjected to further purification to remove branched fatty acids via solvent extraction and over-oxidized byproducts via adsorption (Asinger, 1968). The purified SFAs are subject to esterification with glycerol to produce triglycerides. The reaction may or may not use a catalyst, but uncatalyzed esterification has significant advantages such as continuous operation and averting the need for catalyst addition and separation (Frankenfeld, 1968). The expected yield is in the range of 80% (Frankenfeld, 1968) to 95% (Asinger, 1968). The main esterification reaction is shown in Eq. (3).

$$C_3H_8O_3 + 3\,R-COOH \rightarrow Triglyceride + 3\,H_2O \tag{3}$$

The mixture then undergoes acid and alkali wash followed by bleaching and filtration, which removes any remaining soap traces. As a deodorization process the fat is subject to steaming under heating and vacuum, and filtered again (BIOS, 1946). The product is emulsified with water and subject to chilling, milling and flavoring and coloring with salt, diacetyl and carotene (Frankenfeld, 1968). The final product is considered to contain 78% triglycerides, 20% water and 2% salt and other additives (CIOS, 1945).

Regarding glycerol production, a yield of 90% glycerol from allyl chloride and 85% allyl chloride from propylene are expected (Speight, 2002). The overall reaction from propylene to glycerol is shown in Eq. (4), which encompasses all the relevant reactions taking place: propylene to allyl chloride, chlorine to hypochlorous acid, allyl chloride to glycerol dichlorohydrin and glycerol dichlorohydrin to glycerol (Bagnato et al., 2017; Speight, 2002). Side reactions are taken into account using the reaction yields, but not shown. Sodium carbonate may be used instead of sodium hydroxide.

$$C_3H_6 + 2\,Cl_2 + H_2O + 2\,NaOH \rightarrow C_3H_8O_3 + 2\,HCl + 2\,NaCl \tag{4}$$

2.4. Mass balance

The amount of each feedstock required for a given production capacity is back-calculated via a mass balance based on yields and mass efficiencies from literature, characterized in Section 2.3. The mass efficiency of the separation processes prior to paraffin oxidation and posterior to fractional distillation cannot be generalized as they depend on the nature of the wax feedstock (Asinger, 1968), thus a range of mass losses of 0–20% is assumed for both. A block diagram of the process is shown in Fig. 4, with the relevant data required to estimate the amount of feedstocks required for a given production capacity.

The sodium hydroxide requirements for saponification have been estimated stoichiometrically based on Eq. (2). The glycerol requirements have been obtained stoichiometrically based on Eq. (3) and the final product composition put forth by Williams: the average molecular weight of the fatty acids is estimated as 247.2 from a saponification value of 227 (Williams, 1947; Frankenfeld, 1968). The required amounts of sodium hydroxide and chlorine for glycerol production have been estimated stoichiometrically based on Eq. (4). All estimations include the related reaction yields.

2.5. Assessment of resources required for feeding the global population

The global caloric requirements have been estimated based on a population of 7.8 billion people (United Nations, 2019; Worldometers, 2020) and an average daily caloric requirement of 2100 kcal/day/person (World Health Organization, 2004). The calorific value of the product is considered identical to margarine (DER SPIEGEL, 1947) at 7290 kcal/kg (Nutritionix, 2020). A food waste equivalent to 12% of the total production is taken into account, lower than the current value of ~30% due to decreased food availability during the catastrophe (Denkenberger and Pearce, 2014). The amount of synthetic fat required to fulfill the global caloric requirements is then 933 Mt/year (megatonne per year or millions of tonnes per year).

The US Institute of Medicine proposed a recommended daily fat intake for most adults equaling 20–35% of total caloric intake. In contrast, the World Health organization (WHO) considers that the value should be below 30% to prevent unhealthy weight gain (WHO, 2015) and recommends a minimum of 15% (WHO, 2003, 2008) to ensure fat soluble vitamin absorption. For countries with a level of fat consumption of 15–20% there is no direct evidence for men that raising the value over 20% would be beneficial (Stubbs et al., 2000; Makris and Foster, 2011). Based on this, a reasonably low value of 15% of total caloric intake is set in this work as the target for fulfillment of the global fat requirements. The amount of synthetic fat required to fulfill the global fat requirements is then 140 Mt/year (or 113 Mt dry/year).

Assessing the feasibility of producing enough synthetic fat to fulfill a significant portion of the global food requirements demands analyzing whether the different feedstocks are currently being produced in the required amounts. That is, no scaling up of the industries that produce them would be required. Global propylene production is estimated at 120 Mt/year (Garside, 2019a). Global chlorine production is estimated to have grown to 84 Mt/year in 2020 (Grand View Research, 2016), and the sodium hydroxide production is estimated to have grown to 80 Mt/year (Research and Markets, 2019). Sodium carbonate, which may be used instead of sodium hydroxide, is currently being produced at 60 Mt/year (Garside, 2019b). Sulfuric acid production is expected to reach 278 Mt/year (MarketsandMarkets, 2017).

The potential amount of petroleum wax that could be obtained from current petroleum crude production is estimated from a survey of studies of wax content from crude oil of various origins around the world. Paraffin-rich oils are emphasized, with only oils with a wax content higher than 7% being considered. In total, approximately 37% of the total petroleum crude has been accounted for in the survey, yielding a potential 230 Mt/year of petroleum wax. The actual maximum amount that could be produced by leveraging all wax from current oil production is probably higher, but conservatively only paraffin-rich oils are accounted for. The estimation can be found in Table S6.

2.6. CAPEX estimation

No steady state process modelling simulations were performed in this preliminary study. Thus, no thermodynamic nor chemical kinetic data was used to design the process equipment. Instead, the capital expenditure (CAPEX) of the process is estimated based on literature values. The method used consists of summing the CAPEX of three different production plants involved in the process from wax to fat: an SFA production plant, a synthetic fat production plant and a synthetic glycerol production plant. The power-sizing scaling technique as shown in Eq. (5) is applied to estimate the cost of a plant of the required size based on the CAPEX and production capacity of the known plant (Sinnott, 2005), where C_1 is the unit cost at capacity Q_1, C_2 is the unit cost at capacity Q_2 and x is the cost capacity exponential scaling factor. A target production capacity of 100,000 t/year is selected to leverage economies of scale and produce significant amounts of food quickly.

$$C_2 = C_1(Q_2/Q_1)^x \quad (5)$$

To the best of our knowledge, the only published estimates of the CAPEX of edible fat production via paraffin oxidation can be found in the British Intelligence Objectives Subcommittee report number 805 (BIOS, 1945), which contains the costs of the SFA and fat production plants at approximately 13.4 million *Reichsmark* (RM) for a 40,000 tpa SFA production plant and 0.6 million RM for a 600 tpa SFA to synthetic fat production plant. These are obtained in RM currency from 1944, and then converted to 2020 U.S. dollars using the conversion factors from RM to Euro issued by the Deutsche Bundesbank at €3.8/RM (Bundesbank, 2020) and an exchange rate of $1.2/€. Unfortunately, there is major uncertainty on estimating the value of German currency during the period of interest, with differences of up to twice the value depending on the method used (Bundesbank, 2017). This is accounted for by estimating the range of possible values for the CAPEX within a factor of two.

To the best of our knowledge, there are no publicly available cost estimations of production of glycerol from propylene. The cost of glycerol production is based on an allyl chloride production factory (Govindarajan, 2011), counted twice to account for the capital cost of converting allyl chloride to glycerol. The equipment cost is multiplied by a typical Lang factor of 5 to estimate the CAPEX of glycerol production. The values were updated to current USD via the Chemical Engineering Plant Cost Index (CEPCI). The value of the cost capacity exponential scaling factor for all plants is fixed as $x = 0.6$, a common assumption for chemical production facilities (Sinnott, 2005).

An abrupt sunlight reduction catastrophe would decimate agricultural production abruptly. It would be in humanity's best interest to start production of resilient foods swiftly and early. To this end, fast construction methods are considered, of which constructing around the clock (24/7) is most adequate for the scenario. It reduces overall construction time to 32% of the original at an increased labor cost of 47% (Throup et al., 2021), according to the methodology and values of (Hanna et al., 2007). This value is conservatively incorporated in terms of a 47% increase in the capital cost of the plant to account for labor constraints.

2.7. *Ramp-up speed*

The ramp-up speed is defined here as the increase in the amount of food that can be produced using a given technology by continuously building new factories over time. It depends on the available resources for construction and operation of the plants, and on the available funding for their construction. However, actual budget is not expected to be a constraint given the several trillions spent by governments on economic stimulus after the COVID-19 pandemic struck (Andrijevic et al., 2020), which as a catastrophe is much less severe than an abrupt sunlight reduction scenario. Resource availability is expected to be the limiting factor for ramp-up, which is roughly accounted for in this work by limiting the capital available for new construction of synthetic fat production facilities to the amount invested in construction of chemical-related factories in normal conditions. The CAPEX of chemical and adjacent industries such as power, pulp & paper, utilities and beverages is estimated at 489 billion USD per year (Damodaran, 2020).

Construction time is determined based on historical construction data (Martin et al., 2006) using the facility CAPEX via a reference class forecasting logarithmic correlation, with the construction time of factories as the reference class. Combined with the limited available budget, the amount of reference size plants that can be built at once for a given construction period is estimated. The startup period duration is assumed to be equivalent to one fourth of the construction time at regular speed. During this period an average production capacity of 50% applies (Humbird et al., 2011). An initial delay of 4 weeks is included, similar to the time that complex industries took to scale up production during the COVID-19 pandemic (Betti and Heinzmann, 2020). For the selected target capacity of 100,000 tpa, the ramp-up speed is thus obtained as the rate at which usable production capacity increases over time. This methodology is described more in-depth in (Throup et al., 2021) and (García Martínez et al., 2021c, 2020), particularly in the supplementary material.

2.8. *OPEX estimation*

Operating expenditure (OPEX) of the project includes fixed costs such as maintenance, labor, laboratory costs and overheads. They also include variable costs like feedstock and utility costs. A precise estimation of OPEX would require designing the plant to a FEL-2 or FEL-3 level, which is beyond the scope of this preliminary assessment. Instead, fixed costs have been estimated based on other costs as per the methodology described in Sinnott (2005) and Sinnott and Towler (2019). The values are summarized in Table S5 of Supplementary material.

Feedstock costs can be readily estimated based on mass balance results and the market price of chemicals. A similar analysis is made for potential byproduct revenues. Ideally the synthetic fat production plant would be built within existing refineries with the wax outlet of the crude fractionation column directly connected to the paraffin oxidation section, eliminating the need for wax transport and trading. However, for a conservative estimation here the wax feedstock is considered to be bought at market price to be used in a separate fat production plant. This is the major variable cost of the process, with a value of $600/t based on online vendor quotes.

Utility costs (e.g. electricity and fuel) are estimated here based on the utility usage of historical synthetic fat production plants (BIOS, 1945), which is conservative since energy efficiency in the chemical industry has increased in the last 80 years. The coke oven gas used as gas fuel in the original plants is replaced by natural gas in this work. Energy consumption of glycerol production from propylene is roughly estimated as twice the value of 2.6 kW h/tonne for allyl chloride from propylene (Govindarajan, 2011). The utility consumption and considered price ranges of utilities are summarized in Tables S1 and S2 respectively.

2.9. *Economic analysis*

A net present value (NPV) analysis is performed to estimate the break-even cost of the synthetic fat product. The value is obtained by calculating the revenue needed per unit of fat pro-

Table 2 – Range of the share of global resources required to fulfill the global population's recommended fat requirement of 15% total calories, while accounting for 12% food waste. All mass flows are given for pure compounds.

Variable	Low end	High end	Unit
Synthetic fat production required to fulfill global fat requirements (including food waste)	140	140	Mt/year
Crude wax requirement	203	431	Mt/year
Share of global petroleum wax production potential required	88	187	%
Propylene requirement	8	9	Mt/year
Share of global propylene production required	6	7	%
Chlorine requirement	13	15	Mt/year
Share of global chlorine production required	15	18	%
Sulfuric acid requirement	18	36	Mt/year
Share of global sulfuric acid production required	7	13	%
Sodium hydroxide requirement	27	44	Mt/year
Share of global sodium hydroxide production required	34	55	%
Share of combined global sodium hydroxide and sodium carbonate production required (alkali compounds combined)	22	35	%

Table 3 – Estimated CAPEX ranges for a target size synthetic fat production plant.

	Cost (million USD)	
	Low end	High end
SFA production plant	67	368
SFA to synthetic margarine plant	6	26
Glycerol production plant	32	35
CAPEX	105	429
CAPEX (24/7 construction)	153	626

duced when NPV equals zero. To represent the duration of a strong food shock, 6 years of operation are used instead of the usually longer timelines for chemical plants. The increased CAPEX from 24/7 construction applies. At the end of the 6 year period, the equipment is considered to be depreciated, corresponding to the time of coldest temperatures in the reference model of a sunlight reduction catastrophe (Coupe et al., 2019). In reality, some lower priced food could be sold for longer, there would be some salvage value, or the systems could be built less expensively (less durably), so this is an extremely conservative assumption. The discount rate used to account for the time value of money is 10%, as recommended when in absence of statistical data for the technology (Short et al., 1995). For comparison, the same analysis is performed for normal conditions outside of a catastrophe, namely a typical plant lifetime of 20 years and regular construction cost. Revenue from byproducts is accounted for as part of annual sales prior to tax. The revenue is considered to be taxed by a 35% rate. Financing consisted of 70% equity (10% return on investment), and the remainder a loan with an interest of 8% and a 10 year payment term, in accordance with the financial analysis of (Humbird et al., 2011). Working capital is estimated at 15% of CAPEX, similar to refineries (Sinnott, 2005).

3. Results

3.1. *Assessment of resources required for feeding the global population*

The expected overall mass yield of the process would be between 1.4–3.1 parts of wax required to obtain one part of synthetic edible fat according to the mass balance. This relates to a requirement of 1.3–1.6 parts of wax per part of SFAs, in accordance with historical values for Fischer-Tropsch wax (BIOS, 1946; Zilch, 1968). The amount of wax required to satisfy the global caloric requirements would then exceed the estimated current wax production potential by 6–12 times. For this reason, the focus is on the potential of the synthetic fat to fulfill the global fat requirements instead. The share of global resources that would be required to fulfill the fat requirements of the global population via synthetic fat from petroleum is shown in Table 2 for both ends of the possible range of yields.

Global production of sulfuric acid, propylene and chlorine are not expected to act as a bottleneck to the ramp-up potential of synthetic fats from petroleum for fulfilling fat requirements. A significant share of the global production of the relevant alkali compounds (sodium hydroxide and sodium carbonate) would be required. The available production of petroleum wax could be the limiting factor in terms of resources. Based on the high end of the estimation, petroleum wax production could limit the potential of synthetic fat to fulfilling only around half of the global fat requirement.

3.2. *CAPEX*

The CAPEX ranges for the different production plants involved are summarized in Table 3. The ranged values originate from the different possible values of the yields in each step, since they affect the required amount of each compound and thus the production capacity of the required plant (Q_2). The values obtained are intended as a rough estimation of the CAPEX, with an average value of 267 million USD for a target capacity of 100,000 t/year, or 390 million USD after updating to 24/7 construction. The CAPEX per unit of installed capacity at this scale is estimated between \$1500/tpa (tonne per annum) and \$6300/tpa. Thus, the CAPEX of fulfilling the global fat requirements via 24/7 construction of synthetic fat production plants is expected to be between 0.2–0.9 trillion USD.

The cost of a Fischer–Tropsch facility required for a target size edible fat production plant from coal has been estimated at 4 billion USD based on Kreutz et al. (2008), requiring a total CAPEX one order of magnitude higher than when using petroleum wax. 60 parts of coal would be required per part of synthetic fat produced (Anderson et al., 1954).

3.3. *Ramp-up speed*

The ramp-up speed for the scenario in which the global budget for chemical and related industries can be effectively redirected to fast construction of synthetic fat factories is shown in Figs. 4 and 5. Fig. 5 shows the ramp-up in terms of the global caloric requirements for the mid-range value of expected plant CAPEX. It is presented this way to serve as a comparison with

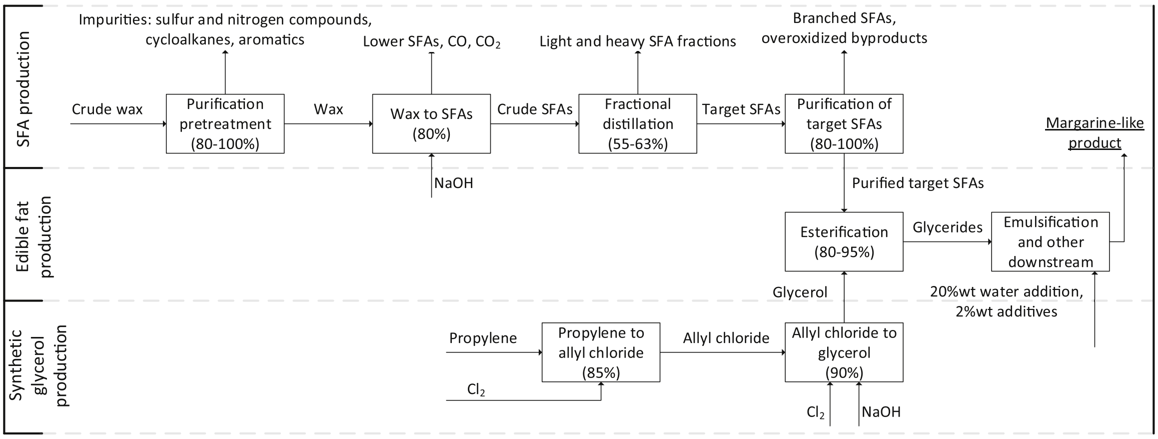

Fig. 4 – Block diagram of the process to obtain edible fat from paraffin wax. The values inside the blocks express the yield or mass efficiency of the step they represent.

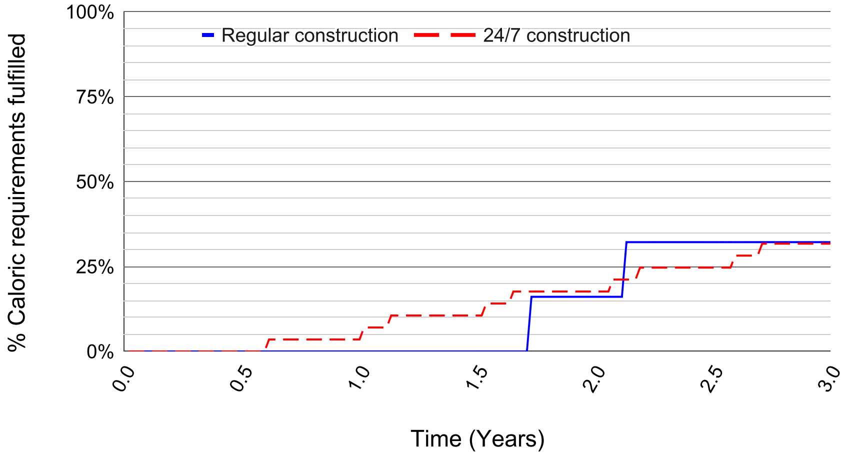

Fig. 5 – Expected ramp-up speed of synthetic fat production in terms of the global caloric human requirements fulfilled over time. The results shown reflect the use of the budget of similar industries, including regular and fast construction speeds.

the ramp-up speeds of other resilient foods, since the amount of available wax production is expected to severely limit the level of synthetic fat production that could be reached.

Fig. 6 shows the ramp-up in terms of the recommended fat requirements for both ends of the range of expected CAPEX. For the fast construction scenario at the end of the first year 2–16% of the caloric requirements could be fulfilled, translating to 15–100% of the fat requirements. The global fat requirements could potentially be covered in approximately 1–2 years. Performing this analysis for coal as a starting material yields around 5% of caloric requirements fulfilled at the end of a 6 year period.

3.4. OPEX

The feedstock costs estimated for a target size fat production plant are found in Table S3. Petroleum wax accounts for over 70% of total variable costs. The potential byproduct revenues are described in Table S4, with an expected average value of 65 million USD. Variable operating costs are estimated within the range of 115–261 million USD/year including utilities, while total OPEX is 152–367 million USD/year, as summarized in Table 4. Waste treatment costs are not accounted for.

3.5. Food price

The NPV analysis is performed to estimate the break-even cost of the synthetic fat product for different scenarios. The expected cost of the fat in catastrophe conditions is estimated by limiting the plant life to 6 years and accounting for the additional cost of 24/7 construction. For comparison, the product cost in normal conditions (20 years of lifetime and regular construction cost) is also obtained. For each of the two scenarios, the product cost is calculated for a low end scenario (low CAPEX and OPEX) and a high end scenario (high CAPEX and OPEX), as lower and upper bounds for the cost. Results are shown in Fig. 7.

A markup of 100% is applied to estimate the retail cost of the fat product, accounting for distribution and other additional costs (McCray, 2010). These values are referred to as a retail cost instead of price due to the uncertain market conditions during a catastrophe, which could alter the sale price. The result is shown in Table 5. Using the same markup value for all prices means that the difference between break-even cost and retail cost may considerably differ between the options. The retail cost for providing the energy equivalent of a person's daily caloric requirements would be $0.74–2.71.

4. Discussion

4.1. *Assessment of synthetic fat from petroleum as a resilient food*

Production of synthetic fat from petroleum is expected to have a somewhat faster ramp-up (in terms of calories) compared

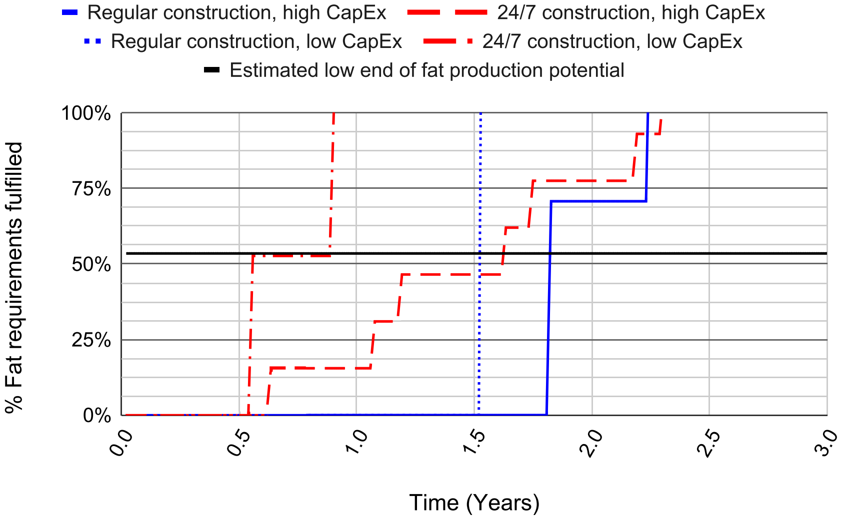

Fig. 6 – Expected ramp-up speed of synthetic fat production in terms of the global recommended fat requirements fulfilled over time, representing both ends of the plant CAPEX range. The results shown reflect the use of the budget of similar industries, including regular and fast construction speeds.

Table 4 – Breakdown of OPEX contributions for a target size synthetic fat production plant of 100,000 t/year capacity.

		Value (million USD/year)	
		Low end	High end
Variable operating costs	Utility costs	11.0	51.3
	Feedstock costs	104.2	209.5
Fixed operating costs		37.2	106.6
Total OPEX		152.4	367.4

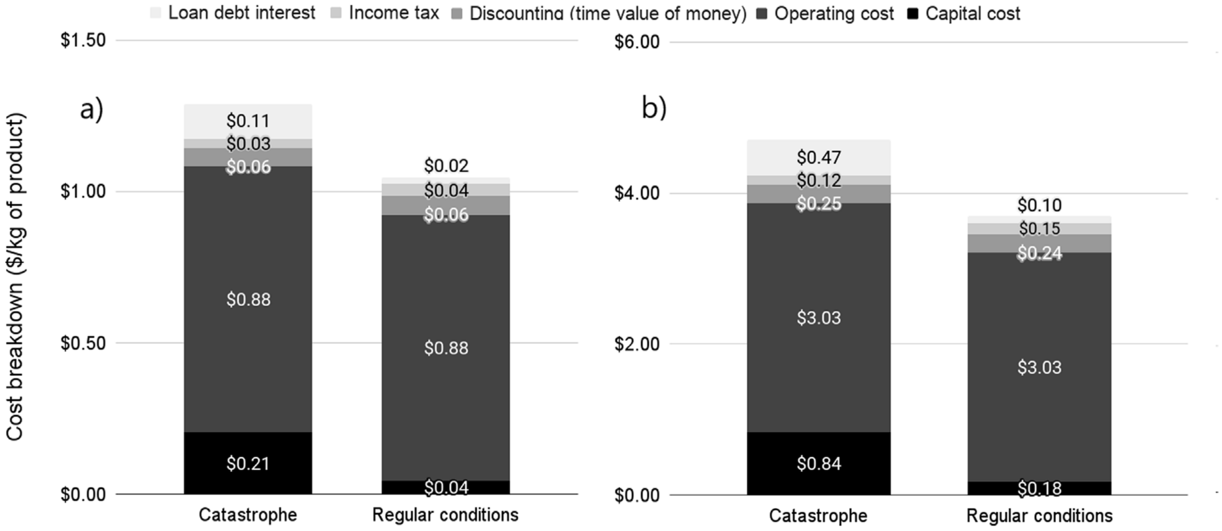

Fig. 7 – Breakdown of the contributions to the wholesale production cost incurred per unit of synthetic fat produced for different scenarios. The low end of manufacturing cost is shown on the left (7a), the high end on the right (7b).

Table 5 – Retail cost of synthetic fat for different fast construction cost scenarios in U.S. dollars per kilogram of (non-dry) fat product.

Scenario	Catastrophe conditions (6 years plant lifetime, 24/7 construction)		Regular conditions (20 years plant lifetime, regular construction)	
Energy and feedstock cost (USD/kg)	Low end	High end	Low end	High end
Wholesale cost	$1.29	$4.70	$1.05	$3.70
Retail cost	$2.58	$9.40	$2.10	$7.40

to other industrial solutions for resilient food production in catastrophes, such as single cell protein production (García Martínez et al., 2021c, 2020), or microbial electrosynthesis (García Martínez et al., 2021b), though it could be slower than production of lignocellulosic sugar, particularly if the existing paper production industry infrastructure is leveraged to this end (Throup et al., 2021). However, non-industrial, low-tech resilient food solutions such as tropical greenhouses

Table 6 – Comparison of synthetic fat from petroleum with other industrial resilient foods and two key low-tech resilient foods (seaweed and greenhouse vegetables) based on three relevant metrics for characterizing the potential of a resilient food. This simplified comparison excludes multiple key considerations which are to be addressed in future work on the topic. These values represent ongoing research and are thus subject to change. All values are given as the average of the estimated range of uncertainty for an approximate comparison. Capital intensity is measured in terms of the capital investment per unit of installed capacity, affordability is measured in terms of the retail cost equivalent to the amount of each food required to fulfill the calories for an average person (2100 kcal), and ramp-up speed is measured in terms of the production capacity installed over time as a share of the total global caloric requirement fulfilled per year, given as a 3-year average. *This is the maximum value that can be achieved by repurposing pulp and paper factories, since their number is limited.

Criteria	Capital intensity	Affordability	Ramp-up speed	Nutritional quality			
Measure	($/t/year)	($/person/day)	(% global caloric requirement/year)	Protein content	Fat content	Micronutritional contribution	Source
Synthetic fat from petroleum	3900	$1.70	10%	–	High	–	This work
Lignocellulosic sugar (new construction)	2500	$1.70	10%	–	–	–	Throup et al. (2021)
Lignocellulosic sugar (repurposed paper factory)	500	$0.50	28%*	–	–	–	Throup et al. (2021)
Methane SCP	4800	$1.60	7%	High	Low	High	García Martínez et al. (2020)
Hydrogen SCP (electrolysis process)	9000	$3.60	4%	High	Low	High	García Martínez et al. (2021c)
Hydrogen SCP (gasification process)	10,500	$2.40	3%	High	Low	High	García Martínez et al. (2021c)
Acetic acid from microbial electrosynthesis	7500	$5.40	2%	–	–	–	García Martínez et al. (2021b)
Low-tech greenhouses in tropical areas (crops)	1600	$3.00	Variable	Variable	Variable	Variable	Alvarado et al. (2020)
Seaweed in tropical areas (Southeast Asia prices)	Variable	$2.20	>100%	Variable	Low	Variable	Ferdouse et al. (2018); Mill et al. (2019)

(Alvarado et al., 2020), seaweed farming in the ocean (Mill et al., 2019), and relocation of cool-tolerant crops are expected to scale up production faster. A comparison of synthetic fat from petroleum with other industrial and low-tech resilient foods is presented in Table 6, presenting criteria relevant for comparison, but leaving out several crucial considerations such as different regional availability of the options, actual resource intensity and the difficulty of comparing these metrics between regular and industrial foods.

The strength of synthetic fat is on its potential to provide a type of macronutrient largely absent in these other resilient foods, making it valuable in preventing malnutrition from a potential fat deficiency. For this reason, a recommendation would be to limit the ramp-up of synthetic fat to the production capacity required to fulfill minimum global fat requirements at most, while the rest of the energy and nutritional requirements are fulfilled by faster scaling and possibly cheaper low-tech resilient food solutions. Even though synthetic fat is expected to ramp up faster than most other industrial resilient food solutions, it is also expected to be significantly limited by the availability of wax feedstock, which would make a higher production target considerably difficult to attain (see Section 4.3).

On average, the expected price per calorie of the synthetic fat is low compared to alternatives, but the amount of the food that can be produced is also expected to be more limited. At the expected price range, around 75–98% of the global population would be able to afford the synthetic fat product for all calories with current incomes (Denkenberger et al., 2019).

4.2. *Technology development roadmap*

This preliminary assessment has uncovered enough potential for synthetic fat from petroleum as a resilient food for catastrophes to warrant further research on the topic. Given how synthetic fat production technology has been practically out of use for several decades, and the technology has never been applied in the exact configuration described here, significant work remains to be done prior to its use in food emergency response. A simplified technology research and development plan is proposed in Fig. 8 in order to clarify key steps towards the proposed application. The plan is designed based on the ultimate goal of leveraging synthetic fat as a resilient food for enabling the possibility of quickly ramping up food production in the event of an extreme food catastrophe. However, it could also apply more broadly to this end for other resilient foods at different levels of technology readiness, in particular for those primarily based on industrial processing technology.

Synthetic fat for human consumption has been obtained from synthetic coal wax, and petroleum wax has been used as a feedstock for SFA production. However, to the best of our knowledge no edible fat has ever been produced from petroleum wax. Proof of concept laboratory experiments would then be a first priority for future research on the topic.

Synthetic fat has been historically used as a food source and has proven nutritional potential, but key concerns of the safety of its use as food remain. Prior to advocating for their use as a resilient food for catastrophes, further laboratory tests and safety studies on acceptable dosage and limits

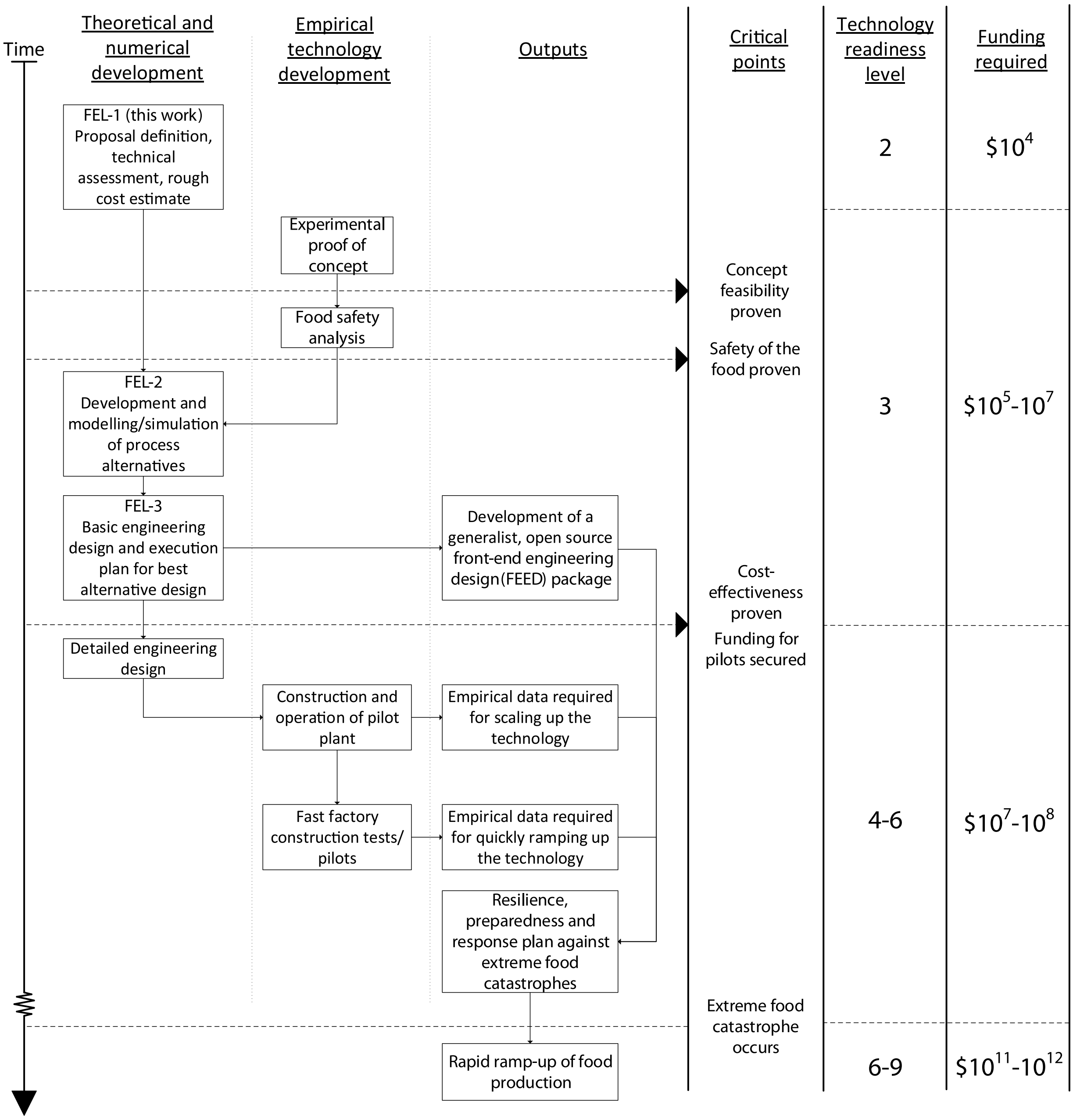

Fig. 8 – Simplified technology roadmap proposed for synthetic fat from petroleum as a resilient food for use in extreme food catastrophes. The 9-level technology readiness scale used here is based on the classification proposed by (Blanc et al., 2017). The funding figures are approximate order of magnitude expected values. This figure and subsection were informed by (Phaal et al., 2004).

of unwanted byproducts would need to be performed. Additionally, the use of continuous processing could be required for consistent product quality, as well as putting strict quality controls in place to keep potentially toxic byproducts in check.

Once proof of concept has been obtained and the necessary food safety studies have been performed, process engineering research and development would be a next step, which would allow for much more precise estimation of capital and operational expenditures. A rigorous chemical and process engineering analysis should be performed at the FEL-2 and FEL-3 stages to identify possible improvements or even alternatives to the historical process that could lead to a more energy efficient, cheaper and/or safer synthetic fat production by leveraging the innovations made in the last 80 years since the original process was created. For example, technologies claiming simpler separation of fatty acids from the USM compared to saponification have been patented (Yamashita and Ninagawa, 1975). Thermal treatment of the oxidate has the desired effect of ester cleavage without saponification taking place (Petrov and Grigor'ev, 1965), implying the presence of esters may not be an impediment to separation methods alternative to saponification. Continuous paraffin oxidation processing improves air oxygen utilization (Freund et al., 1982) and product consistency. More recent reactor configurations boasting a higher fatty acid yield and quality have been proposed (Purohit and Pradhan, 2013). Operating conditions (oxidation pressure, O_2 concentration in gas, gas distribution) could be further optimized (Asinger, 1968). Alternative SFA synthesis routes could also be worth studying e.g. oxidation of primary alcohols or oxocarbonylation of olefins (Fineberg, 1977).

Overall, there appears to be ample room for improvements of the original chemical processes. In addition, a full open source generalist front-end engineering design (FEED) package could be produced with sufficiently accurate CAPEX and OPEX estimates to facilitate global application of the technology if needed. This research and development work could be carried out by academia or industrial consultants.

From here on, in order to further advance the potential of the technology as a resilient food, a degree of funding orders of magnitude higher would likely be required. It is imperative that the cost-effectiveness of ramping-up synthetic fat for emergency response applications is proven based on the engineering assessment, prior to significant investment in the following capital-intensive stages. These developments could be funded publicly as a form of societal techno-economic insurance against GCRs, which would be a global public good.

The updated synthetic fat production process would need to be proven at the pilot stage in order to obtain the necessary data relevant for scaling up the factory size, including commercial product specifications and testing of industrial grade raw materials. Following this, pilot testing of fast construction techniques applied to synthetic fat production facilities could be performed to obtain practical knowledge relevant to quickly ramping up production if catastrophe strikes. This would also help improve evaluation of potential bottlenecks and bring in much more precise estimations of the actual speed at which capacity can be increased. The data generated at these stages could be incorporated into a preparedness and response plan against abrupt sunlight reduction scenarios and other extreme food catastrophes. This could include an analysis of regions well-suited for construction of the production plants and a plan for deployment to a collection of pre-approved sites. Though it would require significant funding, preparation at this stage would arguably be several orders of magnitude cheaper and more cost-effective than building synthetic fat production capacity prior to a food catastrophe.

4.3. *Potential limitations of the potential of synthetic fat as a resilient food*

Potential availability of wax is the most important limitation in terms of inputs, thus a more precise estimation of this value would be advantageous. For example, measurements of the average wax content or productivity estimates for a given boiling range of the desired wax fraction could be obtained from paraffin-rich oil producers. This would help ascertain the degree to which wax availability could hinder the ramp-up of synthetic fat production via paraffin oxidation during a catastrophe.

In order to scale up the feedstock availability further than the current petroleum wax production potential, there would be several options available. First, global production of paraffin-rich crude oil could be scaled up, but it would create an oversupply of the other crude fractions unless their refining and use were also scaled up accordingly. Second, leveraging the global coal production for synthetic fat would allow for fulfilling approximately 13% of the global caloric requirements. This could imply a large oversupply of the co-produced synthetic fuels from coal, and require the construction of an infeasible amount of capital intensive coal liquefaction facilities. Third, the current global syngas production could be leveraged in combination with GTL schemes. Fourth, synthetic fat can also be produced using CO_2 and water via a more complex process (Frankenfeld, 1968). However, none of these options seem particularly cost-effective in terms of food production.

The petroleum wax production potential estimated in this work is based on the wax content of oil, not on how much of the wax fraction is currently being produced. Retrofitting refineries to maximize production of the wax fraction of crude may not be trivial and could require modifications of the crude fractionation process. At worst, it may require the installation of a new fractional distillation column, but retrofitting the column is a more common practice (Wang et al., 2016). Further research on this aspect is needed.

The potential of synthetic fat from petroleum as a resilient food from catastrophes directly depends on the amount of paraffin-containing crude oil being produced at a given moment. If during the next decades petroleum production decreases, the potential for synthetic fat production as a resilient food will decrease accordingly. This could happen for a number of reasons, such as depleting reserves making extraction less profitable or countries making an effort to reduce their greenhouse gas emissions as a measure against climate change. Oil production forecasts predict a reduction in demand in the next decades (DVN GL, 2017; Smith, 2019; McKinsey, 2020; Mirzoev et al., 2020). Thus, the potential of synthetic fat from petroleum as resilient food for GCRs is expected to be somewhat reduced over the coming decades.

The use of the wax fraction of petroleum for manufacturing of synthetic fat would imply competing with current uses of the fraction, of which the most important ones are production of heavy fuel oils and lubricating oils. However, there is the possibility of combining the two main byproducts of the SFA production process, namely the light and heavy fatty acids to create quality lubricants (Asinger, 1968). Other fuels could be used to substitute the use of heavy fuel oil in various applications. Due to the decline of agrichemical fatty acids for soap production caused by a sunlight reduction catastrophe, soap from petroleum wax may emerge as a direct competitor to synthetic fat.

Besides the limitation presented by the amount of wax that could potentially be obtained with existing infrastructure, all other required feedstocks are currently being produced in sufficient amounts to fulfill global fat requirements via synthetic fat production. The propylene, chlorine and sulfuric acid requirements would not represent too significant a share of current global production of the compounds, contrary to the amount of alkali required. Alkali products are versatile chemicals with multiple uses, most of which would likely still be in demand after a sunlight reduction catastrophe. If necessary, a potential solution to avoid scaling global alkali production could be the development of alternatives to saponification with alkali for SFA separation, such as those proposed by Yamashita and Ninagawa (1975) or Maiorov et al. (1971).

4.4. *Nutritional considerations*

A significant lack of fat in the diet can cause deficiencies of fat soluble vitamins, stunted growth, low body weight, dry skin, loss of hair, amenorrhea, mental fatigue and other problems (Hansen et al., 1962) which can be particularly severe in vulnerable groups such as infants, pregnant women and the elderly. A conservative value of 15% of total caloric intake as fat is proposed in this work because its safety is confirmed by evidence (WHO, 2003). To the best of our knowledge, no long-term studies on fat starvation have been performed (Lichtenstein and Van Horn, 1998), making it difficult to pinpoint whether these ailments are caused by a low fat intake or by essential fatty acid deficiency. The body can synthesize fatty acids from carbohydrates via the glycolytic pathway (Stryer et al., 1995), and diets with a high relative carbohydrate intake (55% or more) are safe (Seidelmann et al., 2018), so a reliable supply of these may suffice to avoid the aforementioned nutritional ailments. Thus, the actual minimum amount of total fat in the diet required for the population to survive during a global food catastrophe may be much lower than the proposed value. An historical example can be found in which significant population growth (143%) occurred despite very low fat availability in Rwanda between 1961–1989 with only 4–6% of total recommended caloric requirements covered via fat during this period (Roser and Ritchie, 2013). On the one hand, if the actual bare minimum value of fat intake required for survival is much lower than the value proposed here, fulfilling it via synthetic fat would be faster and use fewer resources that could be invested instead on avoiding protein deficiency (García Martínez et al., 2021c, 2020) for example. On the other hand, it would reduce the significance of synthetic fat as an alternative fat source during catastrophes by making the need for additional fat supply less pressing.

The amount of essential fatty acids present in the synthetic fat is unknown, but likely low or null. These fatty acids are necessary for good health, but the body cannot synthesize them. Some fatty acids are classified as conditionally essential, but only two are known to be truly essential: linoleic acid (an omega-3 fatty acid) and alpha-linoleic acid (an omega-6 fatty acid) (Whitney and Rolfes, 2018). These are both C18 unsaturated fatty acids with a double bond on the 3rd or 6th carbon atom closest to the methyl group at the end of the chain. Some degree of unsaturation is expected in the synthetic fat, for example stemming from the presence of alkenes in the starting material or from the dehydration of hydroxy acids during saponification. Given the complex nature of the process and the dependency of the outcome on the wax feedstock properties, it is difficult to predict how much of the final product will be composed of unsaturated fatty acids and what types will arise. It is uncertain but possible that some small amounts will be omega-3 and omega-6 fatty acids, possibly even containing some essential fatty acids. Experimental research is needed to ascertain this, and also whether it would be possible to increase the content via tuning process conditions or adding new operations. There is research specifically on producing unsaturated fatty acids via paraffin oxidation (Nicolescu, 1958), and on unsaturation of fatty acids via enzymatic treatment (Davidoff and Korn, 1964).

4.5. *Limitations of this research and future work*

This work considers neither the regional distribution of raw materials and supply chain logistics, nor the geo-political and/or social dynamics of a post-catastrophe world. It does not account for the degree of: global coordination, global trade, income continuation, or governmental intervention (e.g. price fixing or rationing). Future research will address these issues.

Note that the financial assumptions used here are common during business as usual, but the financial conditions during a global catastrophe would be complex, likely unpredictable and are outside of the scope of this work. A significant degree of synthetic fat production would affect the market price of both its inputs and byproducts. Further research on market equilibrium during a sunlight reduction catastrophe is expected to help produce more precise price estimations of resilient food prices. However, the apparently low production cost of the synthetic fat product would arguably contribute to increasing affordability and availability of fat sources for those most underprivileged during the catastrophe. Affordable food prices are key for ensuring adequate food access (FAO, 2020), and low-income populations would be the most at risk of starvation in the proposed food catastrophe scenario (Helfand, 2013).

The estimated CAPEX of 0.2–0.9 trillion USD to fulfill the global fat requirements via production of synthetic fat from petroleum is significantly lower than the amount spent by governments on stimulus checks during the COVID-19 pandemic; thus, budgetary constraints are not expected. In a sunlight reduction catastrophe, sunlight would take several years to recover to current levels — 6 years or longer according to published models (Coupe et al., 2019). However, the later the factory is built after the onset of the catastrophe, the fewer years of high value food it would have to operate. The opportunity to operate after the catastrophe would likely be met with negligible demand. Overall, the cost analysis is conservative for the first year's worth of factories.

As discussed in Section 2.6, significant uncertainty is present in the CAPEX calculation, originating from: 1) use of the power-sizing scaling technique (Eq. (5)) to estimate the cost of a factory with a different capacity than the reference factory, which is estimated to have a ±30% accuracy range for plants costing $1–100 million (Peters et al., 2003), 2) ancient capital cost reference values, and 3) conversion of values from *Reichsmark* to USD, which are accounted for in the CAPEX range of 153–626 million USD for a target size plant. As mentioned in Section 4.2, FEED assessments would improve the accuracy of cost estimates. It is worth noting that selecting a different target production capacity other than the proposed 100,000 tpa would yield somewhat different values of CAPEX, product price and ramp-up speed.

It should be noted that the ramp-up speed analysis is conservative in two different ways: first, the capital cost of 24/7 construction is likely overestimated due to applying the increased labor cost factor (Throup et al., 2021) to the entire plant CAPEX value; Second, the chosen budget is likely underestimated. As described in Section 2.7, this analysis effectively uses the industry CAPEX budgets as a proxy for the amount of usable industry resources; in particular, the budget proposed here is based on the chemical and adjacent industries. If human labor and physical assets of the global construction industry could also be efficiently leveraged, the functional budget would be much larger, in turn increasing the speed at which factories could be built. However, sufficient labor availability and equipment construction capacity are not guaranteed in the catastrophe. In addition, the average design and organization delay before action takes place, assumed as 4 weeks, could also be different. More research in these regards would be useful not only for better characterizing the potential of synthetic fat as a resilient food, but also that of most other resilient foods for sunlight reduction catastrophes.

Finally, the dataset used as a reference class for construction time forecasting is based on UK factories. A dataset based on chemical and/or industrial food production factories around the world could yield more precise forecasts.

5. Conclusions

Key contributions of this preliminary assessment to the field of food security in catastrophes are 1) the uncovering of significant potential for synthetic fat from petroleum as a catastrophe-resilient food, and 2) a technology roadmap outlining the future work necessary to verify and develop this potential.

The estimated CAPEX for a synthetic fat production facility based on paraffin oxidation with 24/7 construction is between $1500/tpa and $6300/tpa. The expected retail cost of the product would be in the range of $2.58–9.40/kg, low enough for most of the global population to afford it. The ramp-up time for fulfilling the fat production target is estimated at 1–2 years, meaning it could be achieved relatively early within the duration of the catastrophe. 15–100% of the fat requirements could be covered by the end of the first year, though apparent limitations are highlighted regarding the availability of the main raw material, paraffin wax.

Other resilient food solutions, while generally poor in fat content, would likely ramp up production faster. Thus, the fat production target recommended for synthetic fat is at most 15% of the total food requirement of the global population, according to WHO fat intake guidelines (though the minimum fat requirement for survival appears to be lower).

In the proposed roadmap, proof of concept of the production of synthetic fat from petroleum wax is the first necessary step. Second, food safety studies would have to be performed to ensure absence of significant toxicity risks. Third, a reevaluation of the process engineering part and possibly even the chemistry of the process could be performed in order to uncover potential improvements or alternatives to the historical synthetic fat production process that could lead to increased efficiency, richer nutritional content or better food safety. A generalist plant design package could be produced for a more precise estimation of the required resources and associated manufacturing costs of the synthetic fat. Data from pilot plant testing would provide a basis for the construction of production plants to ramp up food production in a catastrophe. Performing this research would be a global public good; thus it could be funded by public money as a form of societal techno-economic insurance against GCRs.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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