Plasma activated water offers food security opportunities by increasing shelf life of freshwater fisheries products in South Africa

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Abstract

With 40% of the South African population experiencing moderate to severe food insecurity and climate change predicted to impact agriculture negatively, there is a future role for inland fisheries to help feed 60 million people. To support the expansion of inland fisheries, reducing the current postharvest losses of ~25% of fish requires improving the current preservation and storage techniques. This review aims to assess the potential benefits for Sub-Saharan Africa's freshwater aquaculture and fisheries to utilise an emerging technology to reduce postharvest losses, using South Africa as a case study.

We demonstrate the potential for plasma activated water (PAW) for preserving fresh fish. PAW offers non-thermal and non-toxic bacterial inactivation. Considered safe for human use, PAW is currently used in medical applications and has been investigated as a postharvest sanitiser for many fruits and vegetables, effectively increasing the shelf life of fresh food. The limited studies of PAW treatment of fresh fish show increased shelf life with some generally insignificant changes to quality. This novel treatment's success depends on the optimisation of application methods, including PAW-derived ice (PAWDI).

To strengthen the value chain of the fresh fish industry, PAW/PAWDI could extend the shelf life of fish from origin to market. Investment in food supply chain development would preserve more harvested fish and improve the quality. Utilising solar power to produce PAW or PAWDI *in situ* potentially offers benefits for the small communities of inland fisheries to commercial production. This technology as well as changes to traditional preservation and transport chains could be utilised in other Sub-Saharan African nations.

Keywords Cold Plasma; Shelf Life; Food Safety; Sanitiser

1 Introduction

The world's population is growing rapidly (United Nations, 2019), and all countries face the challenge of increasing food output while dealing with the vagaries of climate change. Food insecurity has the biggest effect on the poor, and in the world's poorest countries children and women are the most vulnerable (FAO, 2020). Climate simulations predict losses of arable land and agricultural output in many parts of Sub-Saharan Africa (SSA), which will impact food prices, increasing poverty and food insecurity (Onyutha, 2019).

Small-scale fisheries are recognised for the potential to alleviate poverty and food insecurity (Béné et al., 2007) with aquaculture also contributing via job creation (Béné et al., 2016). Fish is easily digestible, rich in protein, and provides fatty acids, micronutrients, and vitamins (including calcium, phosphorus, iodine, zinc, iron, selenium, as well as vitamins A, B, B12 and D) (Kawarazuka and Béné 2010; Youn et al., 2014; Cyprian et al., 2017). Providing better access to fish for the poor could help reduce chronic and acute malnutrition and stunting in children (Kawarazuka and Bene, 2011; UNICEF, 2013). The increasingly prominent role of inland fisheries and aquaculture should not be overlooked (Lynch et al., 2016), particularly where pelagic fish can be produced, as these are micronutrient-rich (Nölle et al., 2020). Well-managed aquaculture may also provide the most sustainably produced source of animal protein (Lynch et al. 2016) as it has an efficient food conversion ratio of ~2 kg of dry feed to 1 kg of gain. The conversion ratio of aquaculture fish is comparable to poultry (2:1) but better than pigs (4:1) and cattle (7:1) (Brown, 2002; Troell et al., 2004). Freshwater aquaculture could provide a year-round protein and micronutrient-rich food source. However, the reduction of postharvest losses in the supply chain must be addressed.

Plasma, the fourth state of matter, is an ionised gas containing reactive species and ions (Lackmann et al., 2014; Soni et al., 2021). Plasma-activated water is generated by treating water with cold atmospheric plasma (CAP) that, in turn, has been generated by applying an electrical voltage to a carrier gas (Soni et al., 2021). PAW is acidic and has increased electrical conductivity, and the highly reactive oxygen and nitrogen species (RONS) within the CAP are converted to further antimicrobial compounds in water, including hydrogen peroxide, nitrates, nitrites, and peroxynitric acid (Zhou et al., 2018; Perez et al., 2019). The efficiency of PAW is attributed to the combined effect of two or more factors, such as activation time and aeration, which improve the formation of RONS and their dissolution in water (Zhou et al., 2020). PAW has been used as a sanitiser for fruit and vegetables and in medical applications. Commercial PAW systems for production are available for water treatment for livestock (e.g., https://www.ingersollrand.com/en-au/ion-solutions/livestock) and controlled environment agriculture (https://www.ingersollrand.com/en-au/ion-solutions/cea). For postharvest treatment, a roller conveyor type plasma disinfection device has been constructed (Sakudo and Yagyu, 2021). PAW has successfully been used for wound healing, chronic skin infection therapy, dermatology, and cancer therapy (Fridman et al., 2008; Heinlin et al., 2010; Oh et al., 2016). Commercial CP machines available in medicine for treatment of chronic skin wounds and sterilisation, and for dental care and surgery, and sterilisation and listed by Siddique et al. (2019).

This review considered postharvest food loss from inland fisheries in SSA and evaluated the potential of PAW for sanitising inland fish products for distribution to those in food-insecure regions. We briefly examine the current postharvest losses associated with fisheries in selected SSA countries and then explore the development of PAW for inland fisheries to better support food security, with South Africa as a case study.

2 Postharvest losses associated with freshwater fisheries and aquaculture in Sub-Saharan Africa

Few assessments of postharvest loss exist for fish value chains in SSA countries. Losses also differ between fish species and treatment processes (Akande & Diei-Ouadi, 2010; Cheke & Ward, 1998; Mgawe, 2008), resulting in income losses between 32–50% (Cheke & Ward, 1998; Mgawe, 2008). Currently, total African postharvest losses are >25% of the catch (Diei-Ouadi, 2018; Maulu et al., 2020). The reduction of postharvest loss is essential to decreasing food loss, alleviating poverty, and improving nutrition (Affognon et al., 2015) while reducing the environmental impact. Deterioration of fish results in nutrient degradation and contamination with associated increases in the occurrence of foodborne illnesses (Affognon et al., 2015; Kaminski et al., 2020). Quality loss due to damage or spoilage results in fish being sold at a lower price (Ward and Jeffries, 2000). Any food loss or waste in small-scale fisheries reduces the food supply and subsequent nutrient intake, also reducing the income of those along the supply chain (Ward and Jeffries, 2000; Genschick et al., 2017).

Loss can occur at each step of the value chain. Fish can pass through as many as six or seven hands (processing and trading steps) before reaching the consumer. Losses begin at harvesting, where the fish may be damaged due to rough handling or postharvest due to exposure to heat, poor weather, hygiene, and handling practices. Nutritional losses and spoilage occur at processing from poor handling, lack of adequate processing skills (e.g., burnt during smoking) or inefficient facilities (e.g., drying), pest and pathogen damage, and inadequate packaging. The distribution and marketing steps are affected mainly by poor transport chains (poor roads), lack of cooling systems (cold transport, ice), and exposure to extreme heat or rain (Kaminski et al., 2020).

A review of postharvest loss in Ghana, Benin, Tanzania, Malawi and Mozambique reported that the highest losses for fish by quantity were 27% (±14), but this could be halved by implementing strategies to reduce postharvest losses (Affognon et al., 2015). However, this review was limited to only seven published studies, demonstrating the need for more data.

Other reports note that Tanzania's *Rastrineobola argentea* (a pelagic fish) had 32% of physical loss during processing, handling and transportation, equating to 49% economic loss (30% discolouration, 11% bad weather, 8% damage) Mgawe (2008); and the fishing, processing, transportation and storage of Nile perch resulted in physical losses of 4.5–13.5% (Cheke & Ward, 1998).

Zambia’s aquaculture value chain has experienced upgrades in pre-and post-production (Kaminski et al. 2021), mainly initiated by large-scale commercial producers. For instance, some now have ice production, freezing facilities and refrigerated trucks. They are supported by the presence of hatcheries where farming occurs (Genschick et al., 2017). The ~12,000 small-scale Zambian aquaculture farmers fulfil the needs for family consumption, and any surplus fish are directly sold to those with higher incomes in small towns and peri-urban areas, (Genschick et al., 2017). However, a lack of technology for the small-scale aquaculture farmer has forced them to use low-cost fish processing, resulting in losses at processing and along the value chain (Akande & Diei-Ouadi, 2010; Jeffries et al., 2000; Kaminski et al., 2020).

For decades, Ghana has relied on fish for protein (Kent, 1997). Reviewed by Failler et al. (2014), Ghana’s ~4,800 aquaculture ponds include about 3 000 tilapia fish farms, although >90% are small scale non-commercial ponds. The demand for tilapia species is high due to the growing middle class and a local market for all sizes of tilapia. Low technology processing of farmed tilapia and catfish means Ghana suffers losses, and products have a short shelf life due to reduced quality along the value chain. Ghana sustained 42–87% quality losses across the entire value chain (Akande & Diei-Ouadi, 2010). There is a need for innovation in the processing sector, with investment required in processing, packing, and cold chain equipment (Failler et al., 2014).

2.1 Fish Preservation

Fish begin to deteriorate immediately after harvest, and these changes negatively affect the fish’s quality and texture, nutritional content, and edibility (Maulu et al., 2020; Xiang et al., 2020). Harvested fish can spoil and become inedible within 12 hours (Ghaly et al., 2010; Shawyer & Medina Pizzali, 2003). Preservation techniques can increase the shelf life of fish while maintaining nutritional value, texture, and flavour (Ghaly et al., 2010). Successful preservation methods significantly reduce postharvest losses (Funge-Smith & Bennett, 2019), increasing the amount of safe food available for the consumer.

Antimicrobial preservation techniques make the harvested fish an unfavourable environment for microbial growth by changing the pH, temperature, and make-up of the water surrounding, but not bound to, the fish (Ghaly et al., 2010). These methods include thermal and non-thermal techniques as well as synthetic or natural chemical preservatives (Ghaly et al., 2010).

In response to the concerns of consumers, thermal techniques have become widely implemented in preserving fish (Ghaly et al., 2010). Thermal techniques can be highly effective, as heat inhibits microbial growth and can kill heat-sensitive bacteria and simultaneously denature enzymes (Méndez & Abuin, 2012). Energy-intensive, lower temperature techniques are currently the most frequently applied treatments used in the handling and storing fish products (Joardder & Masud, 2019).

In most developing nations, fish from small-scale fisheries are treated using basic postharvest preservation methods (Odoli et al., 2013; FAO, 2016), such as smoking, sun-drying (Kenya; Oduor-Odote et al., 2010a, b), and passive solar drying (Nigeria; Tawari & Abowei, 2011). However, these methods generally do not meet the standards of local food safety regulations (Odoli et al., 2013). Sun-drying can take up to four days depending on the weather and size of the fish, where the fish requires protection from theft and predation by animals and insect infestation (Cole et al., 2018), therefore reducing time for other paid work., Vitamin A is sensitive to heat and sunlight (Kawarazuka and Bene, 2011), which can destroy 90% of the vitamin A in small fish (Chittchang et al., 1999) which reduces the benefits of the products light weight and reduced space required for transportation . (Andersen, 2002). Hot smoking can reduce lysine and other essential amino acids (Kumolu-Johnson et al., 2010). A comparison of the average fish prices in Zambia using the different treatments there showed salted fish was ZMK5 (~US$0.50) more than sundried fish, and an extra ZMK21.3 (~ US$2.10) was paid for iced fish compared to fish wrapped and cooled by water (Cole et al., 2018).

Postharvest chilling with ice (Bensid et al., 2014; Lin et al., 2013; Xuan et al., 2017), or freezing, successfully slows down enzymatic autolysis activity and the growth rate of many bacterial species (Adeyeye, 2017; Shawyer & Medina Pizzali, 2003). However, it does not kill the bacteria, and spoilage activates immediately upon thawing, limiting the shelf life. The aesthetic and nutritional quality of the products may also be negatively affected by a slow freezing rate rupturing the cells (Adeyeye, 2017; Shawyer & Medina Pizzali, 2003). However, communities require access to reliable electricity to power the ice machines and access to refrigeration and freezing facilities wherever possible. This includes access to clean water to make ice, and the requirement for ice-making machines and commercial iceboxes, adding to the cost. In many remote and rural areas, access to these tools is not available, and the absence of power exacerbates the problems for small-scale fishers and farmers.

The constraints of current preservation techniques demand the development of novel preservation methods that maintain the nutritional value of fish while preventing spoilage (Sheng & Wang, 2021). A promising approach that may reduce freshwater aquaculture postharvest losses and health risks is the use of plasma activated water (PAW). Alternative infrastructures such as PAW or PAW derived ice (PAWDI) would allow wider distribution and marketing of fish in domestic and international markets while offering fishers and aquaculture producers bargaining power for their catch, improving their livelihoods.

3 Plasma activated water

Over the last decade, PAW has received considerable interest due to its non-thermal and non-toxic bacterial inactivation ability. PAW is considered safe for human use and is currently used in medical applications (Cha & Park, 2014; Boonyawan, 2017; Xu et al., 2017; Zeltmann & von Woedtke, 2017). Recent reviews of the production and characteristics of PAW (Herianto et al., 2021; Soni et al., 2021; Wang & Salvi, 2021) considered factors such as water source, contact time, AC voltage and frequency, as well as gases and techniques used, for the reduction of microbial pathogens. PAW has been investigated as a postharvest wash treatment for many fruits and vegetables. It can inactivate up to 3 $\log_{10}$ colony forming units (CFU)/mL of different bacterial strains and effectively increases the shelf life of fresh food (Soni et al., 2021). It can be helpful against bacterial spores that are resistant to dehydration and heat treatments (Soni et al., 2021), as bacterial cell membranes are disrupted, and organelles and proteins are damaged. However, the efficiency of PAW cannot be directly compared with >6 $\log_{10}$ CFU/mL reduction of non-spore-forming bacteria by heat treatments such as thermal pasteurisation.

Studies on the use of PAW for the treatment of fresh fish are limited to fresh carp (Esua et al., 2020; Liu et al., 2021), mackerel (Zhao et al., 2020; 2021), and sea bass (Chaijan et al., 2021; 2022) (Table 1). These studies are of significant interest, as freezing of the water is not required before the treatment is applied to the fish product, meaning less infrastructure is required to generate the preservative measure. The trialled water sources included double distilled water (for grass carp) and sterile deionised water (for mackerel and river carp). Different plasma systems generated the PAW, including dielectric barrier discharge, a vacuum system, and an atmospheric cold plasma jet, with air, oxygen, or argon being the generation gases (Table 1). Fish were immersed in the PAW and left static or shaken for a range of times from 2 to 30 min. Despite the differences in water sources, PAW generation method, fish treatment times, and application method, all studies produced comparable positive results.

Table 1: Comparison of fresh fish treated with plasma activated water.

Fish	Treatment details	Observations	Author
Asian sea bass (*Lates calcarifer*) steaks	Vacuum system with oxygen or argon as the feed gas. Water (unspecified source) was treated for 90 min to ensure PAW contained H_2O_2 at 100ppm. Fish treated for up to 120 s, in a ratio of 1:3.	Shelf life at 4°C was extended by suppressing microbial growth below permissible level for 25 days, 15 days more than the controls. Fish quality parameters had minimal changes, except for colour. PAW produced using argon as the feed gas and applied to fish for 30 s was most effective.	Chaijan et al. (2021)
Asian sea bass (*Lates calcarifer*) steaks	Vacuum system with air as the feed gas. Water (unspecified source) was treated for 120 s to ensure PAW contained H_2O_2 at 100ppm. Fish soaked for 120 s, in a ratio of 1:3. Some fish additionally treated with a whey protein isolate and crude ginger extract coating.	The combined treatment of PAW and ginger extract resulted in the shelf life being extended 3.75-fold compared to untreated fish. The combined treatment also had lower rates of volatile compound accumulation throughout storage, and potential reduced lipid and protein oxidation. Discolouration and loss of texture were also reduced. Total psychotropic counts of the combined treated fish remained below the allowable limit for 30 days in cold storage.	Chaijan et al. (2022)
Grass carp (*Ctenopharyngodon idella*) fillets	Dielectric barrier discharge (DBD) system with air as the feed gas. Treated double distilled water or citrate-phosphate buffer (variable voltage up to 70 V and treatment times up to 10 min) to generate plasma liquids. Fillets immersed in cooled plasma liquids for up to 10 min on an orbital shaker.	Plasma liquids made fillets more acidic, and the plasma-treated buffer also negatively impacted colour. Fillets treated with plasma liquids had reduced log CFU/g for *Listeria monocytogenes* and *Salmonella* Typhimurium. Plasma-treated buffers were more effective at reducing bacteria than plasma-treated water. Shelf life was not determined.	Esua et al. (2020)

Mackerel (Scombridae) fillet cubes	Atmospheric cold plasma jet using air as the feed gas. Treated sterile deionised water at 30 kV for 15 min to generate PAW. Cubes of mackerel fillets were submerged for 30 min (static).	Fish quality parameters were not assessed. PAW treated fish cubes had 0.4 log CFU/g reduction of *Pseudomonas fluorescens*. Acidification was noted as essential for PAW to be bactericidal. Shelf life was not determined.	Zhao et al. (2020)
Mackerel (Scombridae) fillet pieces	Plasma jet beam system with air as the feed gas. Both sterile deionised water and peracetic acid were treated for 10 min to activate the liquids. Plasma liquids also combined with ultrasound. Fish submerged for 10 min (static).	No apparent change in fish colour or lipids. Plasma activated peracetic acid and PAW reduced CFU/g for *Listeria innocua*, *E. coli*, and *P. fluorescens*. Plasma peracetic acid suggested as better than PAW if organic material is present. Shelf life was not determined.	Zhao et al. (2021)
Yellow river carp (*Cyprinus carpio*) fillets	Atmospheric pressure plasma jet system with air as the feed gas. Sterile deionised water treated for 120 s to produce PAW. Fish immersed for up to 6 min.	No significant change was observed in fish quality parameters. However, 6 min treatment increased lipid oxidation and decreased pH of fish. Surface colour also changed. Sensory panel determined PAW treated fish no different to fish treated with water. Population of *Shewanella putrefaciens* decreased by up to 1.03 log CFU/g. Shelf life was not determined.	Liu et al. (2021)

The most common finding from these PAW studies was that spoilage organisms associated with fish samples were reduced following immersion in PAW (Table 1). Fresh grass carp (*Ctenopharyngodon idella*) fillets had reduced *Listeria monocytogenes* and *Salmonella typhimurium* populations, with the bacterial numbers correlated with voltages applied during the generation of the PAW (Esua et al., 2020). The higher the voltage applied during the PAW generation, the greater the reduction in bacterial populations. They also reported a more significant decrease in bacterial populations, increasing fish immersion times in the PAW. River carp fillets similarly had reduced populations of *Shewanella putrafaciens* (Liu et al., 2021). Mackerel cubes had reduced *Pseudomonas fluorescens* following PAW treatment, although this was not significant compared to the controls (Zhao et al., 2020). Mackerel pieces had a reduced natural microbiota and inoculated *Listeria innocua*, *Escherichia coli*, or *P. fluorescens* after PAW and plasma activated peracetic acid. Interestingly, the reductions were greater if the plasma liquids were combined with other treatments such as ultrasound (Zhao et al., 2021). Finally, sea bass treated with PAW also had reduced microbial populations, below permissible limits, resulting in treated fish having a shelf life of 15 days longer than untreated fish (Chaijan et al., 2021). When combined with a ginger extract the shelf life was almost four-fold higher than untreated sea bass (Chaijan et al., 2022). All studies noted the potential of PAW as a sanitiser for reducing microbial contamination in fish products.

A single study examining ice production by freezing PAW and its application to shrimp (*Metapenaeus ensis*) reported reductions in bacterial growth, resulting in a doubling of the shelf life of the crustacean (Liao et al., 2018). The results suggested that examining the impact of ice derived from PAW for fish preservation would be valuable, particularly if shelf life is similarly extended. Notably, the PAW derived ice (PAWDI) was also reported to delay changes in colour (particularly alleviating progress of melanosis) and texture, and it did not degrade proteins. The production of volatile basic nitrogen was also reduced compared to shrimp preserved with ice produced from tap water. Katsaros et al. (2021) warned that ice must be microbiologically and chemically safe because it directly contacts food products and can be consumed. They noted that PAWDI is effective for the storage and shelf life of sea bream and sea bass fillets, although this work has not been published.

Several studies have also investigated cold plasma as a direct treatment for various fish products rather than for treating water. However, cold plasma can be generated using different systems, making comparing studies difficult. Fish that have been trialled include two species of mackerel, herring, bass, bream, and tilapia (Albertos et al., 2017; Albertos et al., 2019; Chen et al., 2019; Giannoglou et al., 2020; Mohamed et al., 2021; Olatunde et al., 2021a; Wang et al., 2022), and crustaceans including shrimp and crab (Olatunde et al., 2021b; Sheikh & Benjakul, 2020). We only discuss tilapia here for brevity as this fish is widely caught and consumed in SSA. Mohamed et al. (2021) treated fresh whole tilapia (*Oreochromis niloticus* syn. *Tilapia nilotica*) with cold plasma using a mains-powered dielectric barrier discharge system, with the fish placed between the two electrodes. One concern was that if the gap between the electrodes was reduced, the treatment could burn the fish. However, when this gap was adjusted to avoid burning, the fish had an increased shelf life of up to 10 days, with decreased microbial pathogens, and the organoleptic properties were maintained. Wang et al. (2022) treated *O. mossambicus* and similarly reported a decreased in both number and diversity of microbial pathogens, with a shelf life of 12 days at 4°C. This improvement is significant given the value of *Tilapia* in various African countries.

It is important when assessing a new food preservation method to determine that the quality parameters of the commodity are not adversely impacted. The impact of PAW on fish colour was determined for grass carp fillets, with significant changes reported depending on the liquid used (Esua et al., 2020). The acidity of the fillets also increased; however, it was not significant. The authors did not conduct any quality evaluations in their study. Similarly, in river carp, changes were observed in the colour and acidification of the PAW treated fillets in addition to significant lipid oxidation (Liu et al., 2021). However, no significant changes occurred to sensory properties or texture attributes when compared to fish treated with water only. In contrast, for mackerel, colour and lipid oxidation (measured by peroxides and thiobarbituric acid reactive substances) were not significantly different to water-treated controls (Zhao et al., 2021); however, other quality parameters were not reported as they did not measure any sensory properties or texture. In sea bass, comprehensive quality tests were measured (Chaijan et al., 2021), including off-flavour volatiles (including sulphides, ketones, alcohol, and aldehydes), lipid and protein oxidation, and pH, colour, texture, and moisture drip. It was found that PAW-treated bass steaks appeared to have reduced off-odour and off-flavour development with minimal oxidation of lipids and proteins compared to non-treated controls; however, heme iron content was reduced, colour varied, and some loss of texture was noted (Chaijan et al., 2021). The reduction in iron is a concern as this is a critical nutrient in SSA countries, particularly for children (Akalu et al., 2021), so would need to be monitored in all treatments. When PAW was combined with a ginger extract coating, the quality was significantly improved (Chaijan et al., 2022). While the studies reviewed here suggest that some changes occurred following the treatment of fish with PAW, they were not considered significant in most instances. Esua et al. (2021) compared the use of functionalised water by electrolysis, ozone, and cold plasma, and encouraged the use of PAW in future applications.

The plasma generation systems used in the above studies range from custom-built equipment to off-the-shelf commercial systems. The various systems have been reviewed (Herianto et al., 2021; Soni et al., 2021; Wang & Salvi, 2021), and it is important to note that the power consumption used for generating cold plasma should not be a limiting factor. A handheld battery-operated plasma source, with integrated solar-power charger has been effective for microbial decontamination (Ni et al., 2016), and other battery-operated devices exist (Pei et al., 2014; Usta et al., 2019). Plasma technology presents a safe way to reduce microbial contaminants without the need for chemical treatments. Plasma technology has human health and environmental benefits, particularly when plasma can be generated using solar power rather than electricity. A standalone plasma generation system can be fabricated for ~US$500, plus labour, using readily available components; a standard 24V folding solar panel to charge a combination battery/inverter pack which energises a repurposed neon light 10000V power supply. The container can be constructed using a standard backpack pressure sprayer modified to hold a discharge arc vessel (glass jar) with the spray nozzle directed back into the tank. With the potential of utilising PAW in clinical settings, fruit and vegetable washes, and for freshwater fish sanitisation, villages or community groups could produce PAW on a user pays basis and help reduce food-borne illness.

3.1 Potential for PAW in SSA inland fisheries –South African case study

Barkhuizen et al. (2016) reviewed fishery initiatives in the Free State Province (1979–2014) accessing catch data from 7 locations: Bloemhof, Kalkfontein, Gariep, Vaal, Erfenis, Rustfontein and Koppies Dams. On average, 282 (±185) t/year of fish were caught, mainly common carp *Cyprinus carpio* and *Labeo capensis* and *L. umbratus*. Only two commercial fisheries were sustained for more than ten years, while the rest failed due to low yields, low local demand for freshwater fish, and limited refrigeration capacity. No permanent jobs were created; all employed casual labour. Attempts to develop a small-scale fishery at Gariep Dam have also failed. Three government-supported projects only operated for a few months in the year, and unrealistic yield expectations, poor management capacity and market constraints were blamed for their failure (Barkhuizen et al., 2016). The inability to develop sustainable commercial inland fisheries in South Africa indicates that small-scale fishers and aquaculture need to be supported due to their benefits to the poor and their contribution to food security.

In contrast to the commercial failures, a 15-month study at Lake Gariep completed in December 2007 gathered information via questioning anglers (*n*=357; Ellender et al., 2010). Subsistence anglers (99%) living within 10 km, with <30% permanently employed, were found to be predominantly reliant on the resource for food (53%) and as a primary or supplementary source of income (41%). The Lake Gariep fishery provides important food security to some rural poor and demonstrates the potential for small scale fishers to overcome food insecurity.

However, in Limpopo Province in the northeast of the country, Drimie and McLachlan (2013) reported one of the highest numbers of households experiencing hunger due to low income. In the mid-2000s Limpopo had ~5.55 million people, which was 10% of South Africa's total population (Statistics South Africa, 2008). Surveys in 2011 in 5 districts investigating almost 600 rural households showed that 80% of rural households were moderate to severely food insecure (De Cock et al., 2013). About 90% of the people were in rural areas, where 92% have electricity connected (De Cock et al., 2013).

The Limpopo River basin has the highest native fish species richness in South Africa (Weyl et al., 2021). Unfortunately, many of the river systems are polluted with pesticides, hydrocarbons, and metals (lead, chromium and arsenic), that leach into the water supply from agriculture and mining activities. Metals over the recommended levels for safe consumption have accumulated in the fish (Addo-Bediako et al., 2014; Barnhoorn et al., 2015; Weyl et al., 2021). Regular consumption (a weekly 150 g portion) of these contaminated fish could cause genotoxic and carcinogenic damage (Du Preez et al., 2003). With limited studies of residue levels in fish, the risk factors for all the systems with fisheries potential remain unknown (Weyl et al., 2021). Plasma treatment can be used to treat contaminants, in soil and water (Kumar et al., 2021; Qu et al., 2013; Zhang et al., 2017), offering a potential solution. Cold plasma generates reactive species which can degrade pesticides without added polluting chemical agents (Kumar et al., 2021). The production of free radicals during plasma generation combined with activated carbon can remove cadmium and phenols from water (Qu et al., 2013) while others have shown success in remediating contaminated soils (Zhang et al., 2017).

Food-borne illnesses are widespread, and fish could be a causal agent. The prevalence of food-borne illness was studied for two years in three Eastern Cape villages (2012-2014) and revealed that 27% of people surveyed had fallen ill during the study period. More than half did not seek medical treatment, and of those who did, only 20% were recorded by clinics (Bisholo et al., 2018) meaning that these types of illnesses are under reported. Treatment of farmed or wild caught fish using PAW could make this food source a safer option.

Food insecurity must be addressed to deliver on the South African constitution, which promises citizens a right to food and safe water (Hendriks, 2005; Masipa, 2017; Termeer et al., 2018), primarily for the rural and other poor people. While South Africa recognised the future role of inland fisheries for feeding the 60 million people in the 1990s (FAO, 1997; Hara & Backeberg, 2014; World Bank, 2021), by 2016, inland fisheries remained severely underdeveloped, with less than 1% of the total fish caught from freshwater (FAO, 2018; McCafferty et al., 2012). Freshwater aquaculture has been targeted for development to provide sufficient, safe, and nutritious food that is affordable and available to all South Africans (DFFE, 2020; Masipa, 2017). Twenty-one strategic surface water source areas have been identified (Figure 1), covering 8% of South Africa and supplying 50% of the mean annual runoff (CSIR, 2021). A significant proportion of the water catchments will have increased freshwater due to the predicted increase in rainfall (Figure 2), providing the opportunity to develop inland aquaculture.

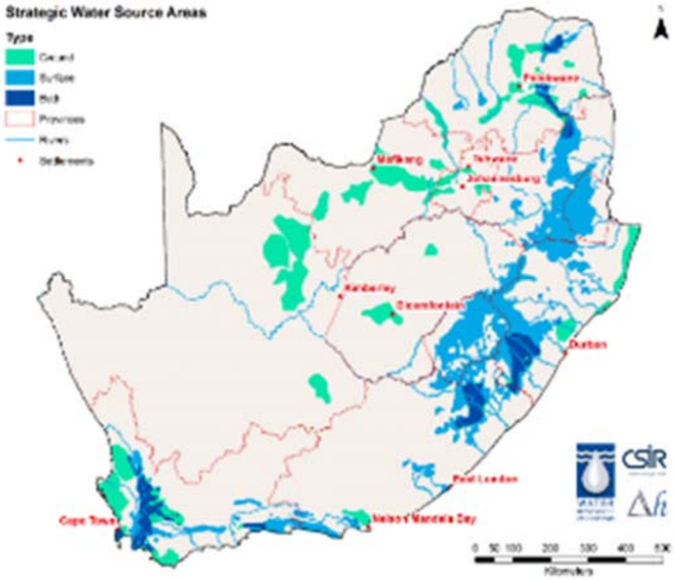

Figure 1: Water source areas of South Africa 2019 (CSIR, 2021).

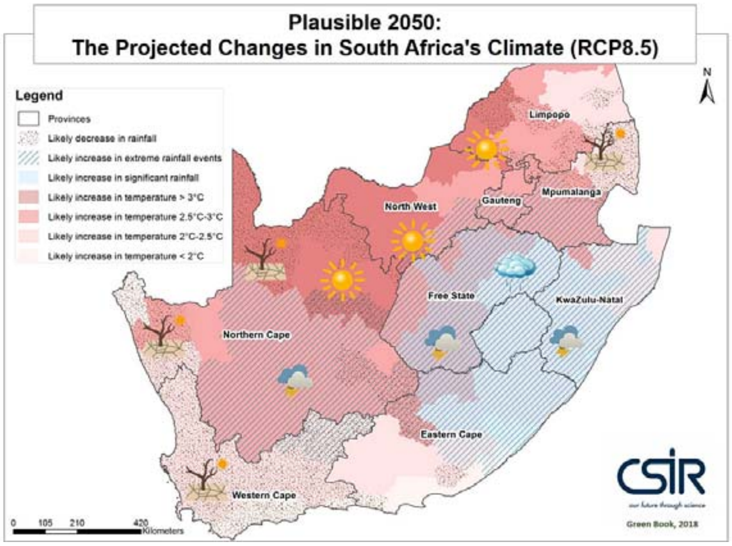

Figure 2: Projected climate change in South Africa by 2050 (from Van Niekerk et al., 2019)

With increasing temperature, some freshwater aquaculture fish species grow faster, such as the Nile tilapia (*O. niloticus*) (Muchuru & Nhamo, 2018). The increasing temperature may create areas at a higher elevation suitable for aquaculture, and higher rainfall may increase the potential for aquaculture in previously marginal areas (Muchuru & Nhamo, 2018). An increased frequency and duration of rainfall in some areas due to global change will potentially increase an aquatic system's overall productivity as it has access to more resources, such as nutrients, for longer (Welcomme et al., 2010). Unfortunately, raised temperatures will increase the survival of bacteria and parasites (Welcomme et al., 2010). Microbial contamination will become more prevalent as temperatures rise (Hammond et al., 2015), exacerbating the incidence of food loss. Increasing temperatures caused by climate change will threaten the whole value chain of the fresh fish industry; therefore, treatments such as PAW can be applied to extend the lifespan of safe storage from origin to market.

There is a paucity of information on South Africa's inland water sources and the fish and fisheries (McCafferty et al., 2012). Small-scale inland fisheries are poorly developed (McCafferty et al., 2012) due to the low productivity of inland waters

(DFFE, 2021). The Free State, Eastern Cape, and North-West Provinces have promoted small-scale livelihood fishing projects on an ad-hoc basis (McCafferty, 2012); however, due to a lack of government support, including access to value-adding opportunities and markets, it has been difficult to create sustainable livelihoods (Britz, 2015). However, in the value chain approach of the National Freshwater (Inland) Wild Capture Fisheries Policy, it is promised that “small-scale fishers will be assisted with both resources and technical support to reduce postharvest losses, meet sanitary requirements and achieve their marketing objectives” (DFFE, 2021). The fishers would benefit from access to PAW so that they may sanitise larger fish and increase their income.

South African inland aquaculture can contribute to food security directly, and indirectly through job creation (DFFE, 2021). For instance, one person is employed for each 4 t of Zambia’s aquaculture production, the feed and seed sectors provide jobs, and informal downstream value chain jobs help to reduce poverty, for instance, street vendors selling fish in urban areas (Genschick et al., 2018). Three major tilapia aquaculture producers in Ghana employ 230 people and produce 8,600 t annually (38 people/t) (Failler et al., 2014). For each tonne of fish produced in Egypt, there are ~1.4 full-time equivalent jobs (Mcfadyen et al., 2012). Small-scale aquaculture employs unskilled manual labour, digging ponds and netting fish (Kaminski et al., 2021), alleviating food insecurity by providing income.

Maximising the contribution of aquaculture and fisheries to food security requires moving toward more environmentally sustainable practices and carefully balancing social and economic concerns with a focus on the aquaculture of finfish species (FAO, 2019). Agriculture could be encouraged to include aquaculture in its programming. Appropriate policies to create favourable environments are required to strengthen sustainable inland aquaculture. These include the reduction of postharvest losses and a focus on better distribution of fish; developing private feed and seed industries and hatcheries; diversifying fish species; and focusing both on fish species with high commercial value (Chan et al., 2019) and those in demand from local consumers. Babatunde et al. (2021) identified the need to prioritise the development of the aquaculture industry, focusing on “enabling private sector participation, uptake of new technologies for aquafeed production and farm management, the commercialisation of aquaculture, and reducing the supply gap”.

They proposed that government and industry support aquaculture development with “access to affordable credit, sufficient quality and quantity of inputs, and land ownership”. Adeyeye (2017) suggested that achieving food security would require increases in the quantity of fish (by improved food processing and storage and effective distribution systems), particularly pelagic fish, and incomes to purchase food. There is potential for small aquaculture farms to benefit from the niche market for small pelagic fish, if they can use PAW to sanitise rather than the time consuming and often unsanitary drying methods.

However, in many countries, including South Africa, large-scale commercial development of inland aquaculture does not increase food security for lower-income consumers or small producers, as produce leaves the area for other markets or is too expensive (Cisneros-Montemayor et al., 2016), and the higher value fish do not necessarily provide high levels of micronutrients (Bogard et al., 2017). To support the poor and decrease food insecurity, a living wage for those in freshwater fisheries is needed to enable the fisher to support their family and enable sustainable practices (Cisneros-Montemayor et al., 2016). However, Africa has 58 to 82% of fishers living below the minimum living wage in their country (Giron-Nava et al., 2020). By improving access to enhanced technologies and knowledge, productivity increases could be achieved in small-scale aquaculture, creating more on-farm jobs and resulting in a stronger uptake of aquaculture into rural communities (Kaminski et al., 2021). Where hatcheries and feed stores exist, support hubs to include PAW could be set up for aquaculturists.

4 Conclusion

With an efficient food conversion ratio, freshwater commercial aquaculture can provide a year-round protein and micronutrient-rich food source for all SSA countries. However, postharvest losses in the supply chain need to be reduced. PAW or PAWDI can potentially reduce nutritional losses and spoilage, to produce a safer product with increased shelf life with little change to aesthetics. While PAW/PAWDI may only be immediately accessible to commercial aquaculture, and a trickle-down effect is likely to occur for the poor via the creation of jobs in the production of fish, feed and seed, and buying and selling of fish down the value chain. In regions suitable for aquaculture, the supporting industries could be located together as already occurring in some countires,and include PAW stations. Small-scale fish farmers, traders, and agriculturists could access PAW/PAWDI and technical support for their PAW systems. Once there is technical expertise in the region, then villages could consider purchasing solar powered PAW machines utilising the support of the National Freshwater (Inland) Wild Capture Fisheries Policy, or PAW/PAWDI distributors could be established so that they can deliver these sanitising products.

The availability of freshwater fish to the rural and urban poor can increase food security in South Africa as fish are easily digestible and rich in protein, fatty acids, and vitamins. Increased consumption of pelagic fish can reduce malnutrition and stunting in children. Previous attempts to establish inland fisheries in South Africa have failed, and the poor tend to overfish or take juveniles as they can be dried. To enable the poor to install and operate aquaculture can protect the environment and populations of wild fish. The commercial sector markets >300 g fish, but the rural and urban poor represent a market for smaller fish (100 - 300 g). Thus, providing an opportunity for a niche market for small-scale farmers using minimal inputs, allowing them to sell fish grown on low-cost feeds rather than wild-caught juvenile fish. Small fish can be dried and stored for an extended period. They are more affordable as they can be purchased in small quantities and are easily divided among household members. However, the drying process is time-consuming and results in losses. PAW can address the National Freshwater (Inland) Wild Capture Fisheries Policy's aim to assist small-scale fishers with resources and technical support to reduce postharvest losses and meet sanitary requirements. While increasing the shelf life and providing a longer marketable time to sell for the right price, the poor will not be at the mercy of manipulative traders.

Currently, for the subsistence fishers and small-scale aquaculturists, the lack of infrastructure and transportation dictates the processing required; otherwise, the catch must be sold within the same day as capture. Ideally, using ice made from clean water would help reduce postharvest losses and food-borne illnesses; however, this is beyond the reach of many SSA communities without reliable electricity to make ice or to have access to refrigeration. PAW provides an innovative solution for processing fish caught or farmed in remote areas by providing the ability to sanitise the fish products for distribution in those food-insecure regions. A solar-powered, handheld plasma source has been effectively used for microbial decontamination, and we propose that solar powered kits using readily available components can be compiled for under US$500, making this an affordable system for communities in remote regional areas in SSA.

Acknowledgements

The authors acknowledge the financial support provided by the Australia Africa Universities Network. We thank Steve Gregg for his pre-design concept and estimates for solar-powered PAW kits.

Declarations

Funding: This study was funded by the Australia Africa Universities Network. Both Henneke and Chalwin-Milton received a stipend from this funding.

Financial interests: The authors declare they have no financial interests relevant to the content of this article.

Competing interests: The authors have no competing interests to declare that are relevant to the content of this article.

Author contributions: The three senior authors (Oosthuizen, Johnston, and Bayliss) contributed to the study's conception and design and were awarded the funding. The literature review and preparation of relevant material arising from the review were conducted by Kay Howard, Frederich Henneke, Olivia Chalwin-Milton and Kirsty Bayliss. The first draft of the manuscript was prepared by Kay Howard. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

Addo-Bediako, A., Marr, S. M., Jooste, A., & Luus-Powell, W. J. (2014). Human health risk assessment for silver catfish *Schilbe intermedius* Rüppell, 1832, from two impoundments in the Olifants River, Limpopo, South Africa. *Water SA*, *40*(4) 607- 613. http://dx.doi.org/10.4314/wsa.v40i4.5

Adeyeye, S. A. O. (2017). The role of food processing and appropriate storage technologies in ensuring food security and food availability in Africa. *Nutrition & Food Science*, *47*(1), 122-139. https://doi.org/10.1108/NFS-03-2016-0037

Affognon, H., Mutungi, C., Sanginga, P., & Borgemeister, C. (2015). Unpacking Postharvest Losses in Sub-Saharan Africa: A Meta-Analysis. *World Development, 66*, 49–68. http://dx.doi.org/10.1016/j.worlddev.2014.08.002

Akande, G., & Diei-Ouadi, Y. (2010) Post-harvest losses in small-scale fisheries: case studies in five sub-Saharan African countries. FAO Fisheries and Aquaculture Technical Paper. No. 550. Rome, FAO.

Akalu, Y., Yeshaw, Y., Tesema, G. A., Demissie, G. D., Molla, M. D., Muche, A., Diress, M., & Tiruneh, S. A. (2021). Iron-rich food consumption and associated factors among children aged 6–23 months in sub-Saharan Africa: A multilevel analysis of Demographic and Health Surveys. *PLoS ONE 16*(6), e0253221. https://doi.org/10.1371/journal.pone.0253221

Albertos, I., Martín-Diana, A. B., Cullen, P. J., Tiwari, B. K., Ojha, S. K., Bourke, P., Álvarez, C., & Rico, D. (2017). Effects of dielectric barrier discharge (DBD) generated plasma on microbial reduction and quality parameters of fresh mackerel (*Scomber scombrus*) fillets. *Innovative Food Sciences Emerging Technology, 44*, 117–122.

Albertos, I., Martin-Diana, A. B., Cullen, P. J., Tiwari, B. K., Ojha, K. S., Bourke, P., & Rico, D. (2019). Shelf-life extension of herring (*Clupea harengus*) using in-package atmospheric plasma technology. *Innovative Food Science & Emerging Technologies, 53,* 85–91.

Andersen, O. (2002). Transport of fish from Norway: energy analysis using industrial ecology as the framework. *Journal of Cleaner Production, 10*(6), 581-588. https://doi.org/10.1016/S0959-6526(01)00057-9

Babatunde, A., Robertson-Andersson, D., Moodley, G., & Taylor, S. (2021). A quantitative SWOT analyses of key aquaculture. *Aquaculture International, 29***,** 1753–1770. https://doi.org/10.1007/s10499-021-00715-4

Barkhuizen, L. M., Weyl, O. L. F., & van As, J. G. (2016). A qualitative and quantitative analysis of historic commercial fisheries in the Free State Province in South Africa. *Water SA, 42* (4), 601-605. http://dx.doi.org/10.4314/wsa.v42i4.10

Barnhoorn, I. E. J., van Dyk, J. C., Genthe, B., Harding, W. R., Wagenaar, G. M., & Bornman, M. S. (2015). Organochlorine pesticide levels in *Clarias gariepinus* from polluted freshwater impoundments in South Africa and associated human health risks. *Chemosphere, 120*, 391–397. https://doi.org/10.1016/j.chemosphere.2014.08.030

Béné, C., Macfadyen, G., & Allison, E.H. (2007). Increasing the contribution of small-scale fisheries to poverty alleviation and food security. FAO Fisheries Technical Paper, No. 481. Rome, FAO. pp141.

Béné, C., Arthur, R., Norbury, H., Allison, E., Beveridge, M., & Bush, S. (2016). Contribution of fisheries and aquaculture to food security and poverty reduction: Assessing the current evidence. *World Development*, *79*, 177–196.

Bensid, A., Ucar, Y., Bendeddouche, B., & Özogul, F. (2014). Effect of the icing with thyme, oregano and clove extracts on quality parameters of gutted and beheaded anchovy (*Engraulis encrasicholus*) during chilled storage. *Food Chemistry*, *145*, 681–686. https://doi.org/10.1016/J.FOODCHEM.2013.08.106

Bisholo, K. Z., Ghuman, S., & Haffejee, F. (2018). Food-borne disease prevalence in rural villages in the Eastern Cape, South Africa. *African Journal of Primary Health Care & Family Medicine, 10*(1), a1796. https://doi.org/10.4102/ phcfm.v10i1.1796

Bogard, J. R., Farook, S., Marks, G. C., Waid, J., Belton, B., Ali, M., Toufique, K., Mamun, A., & Thilsted, S. H. (2017). Higher fish but lower micronutrient intakes: Temporal changes in fish consumption from capture fisheries and aquaculture in Bangladesh. *PLoS ONE, 12*(4): e0175098. https://doi.org/10.1371/journal.pone.0175098

Boonyawan, D. (2017). Innovative research of plasma physics for life sciences. Journal of Physics: Conference Series 860, 012030.

Britz, P. (2015). The history of South African inland fisheries policy with governance recommendations for the democratic era. Water SA, 41(5), 624-632. http://dx.doi. org/10.4314/wsa.v41i5.05

Brown, L. R. (2002). Feeding everyone well: restructuring the protein economy. Eco-economy: Building an economy for the earth. Orient Blackswan.

Cha, S., & Park, Y.-S. (2014). Plasma in dentistry. *Clinical Plasma Medicine, 2,* 4–10.

Chaijan, M., Chaijan, S., Panya, A., Nisoa, M., Cheong, L.-Z., & Panpipat, W. (2021). High hydrogen peroxide concentration-low exposure time of plasma-activated water (PAW): A novel approach for shelf-life extension of Asian sea bass (*Lates calcarifer*) steak. *Innovative Food Science & Emerging Technologies, 74,* 102861. https://doi.org/10.1016/j.ifset.2021.102861

Chaijan, M., Chaijan, S., Panya, A., Nisoa, M., Cheong, L.-Z., & Panpipat, W. (2022). Combined effects of prior plasma-activated water soaking and whey protein isolate-giner extract coating on the cold storage storability of Asian sea bass (*Lates calcarifer*) steak. *Food Control, 135*, 108787

Chan, C. Y., Tran, N., Pethiyagoda, S., Crissman, C. C., Sulser, T. B., & Phillips, M. J., (2019). Prospects and challenges of fish for food security in Africa. *Global Food Security, 20,* 17-25. https://doi.org/10.1016/j.gfs.2018.12.002

Cheke, R. A., & Ward, A. R. (1998). A model for evaluating interventions designed to reduce postharvest fish losses. *Fisheries Research, 35*(3), 219–227.

Chen, C., Liu, C., Jiang, A., Guan, Q., Sun, X., Liu, S., & Hu, W. (2019). The effects of cold plasma-activated water treatment on the microbial growth and antioxidant properties of fresh-cut pears. *Food and Bioprocess Technology*, *12*(11), 1842–1851. https://doi.org/10.1007/s11947-019-02331-w

Chittchang, U., Jittinandana, S., & Sungpuag, P. (1999). Recommending vitamin A-rich foods in southern Thailand. *Food Nutrients Bulletin, 20*, 238–242.

Cisneros-Montemayor, A. M., Sanjurjo, E., Munro, G. R., Hernández-Trejo, V., & Sumaila, U. R. (2016). Strategies and rationale for fishery subsidy reform. *Marine Policy*, *69*, 229–236. https://doi.org/10.1016/j.marpol.2015.10.001

Cole, S. M., McDougall, C., Kaminski, A. M., Kefi, A. S., Chilala, A., & Chisule G. (2018). Postharvest fish losses and unequal gender relations: drivers of the social-ecological trap in the Barotse Floodplain fishery, Zambia. *Ecology and Society 23*(2):18. https://doi.org/10.5751/ES-09950-230218

CSIR (2021) Strategic Water Source Areas of South Africa. CSIRO Newsletter. https://www.csir.co.za/strategic-water-source-areas-south-africa. Accessed Nov 2021.

Cyprian, O. O., Nguyen, V. M., Sveinsdottir, K., Tomasson, T., Thorkelsson, G., & Arason, S. (2017). Influence of blanching treatment and drying methods on the drying characteristics and quality changes of dried sardine (*Sardinella gibbosa*) during storage. *Drying Technology*, *35*(4), 478–489. https://doi.org/10.1080/07373937.2016.1187161

Department of Forestry, Fisheries and the Environment (DFFE). (2020). Report of the Official Guide to South Africa 2019/2020: Environment, Forestry and Fisheries. Pretoria, Gauteng.

Department of Forestry, Fisheries and the Environment (DFFE). (2021). National freshwater (inland) wild capture fisheries policy for South Africa. Accessed 25/6/2022 https://www.dffe.gov.za/sites/default/files/legislations/wildcapturefisheriespolicy.pdf

Diei-Ouadi, Y. (2018). Post-harvest losses in inland fisheries. In S. J. Funge-Smith (Ed.), *Review of the state of world fishery resources: Inland fisheries* (pp. 206–215). FAO Fisheries and Aquaculture Circular No. C942 Rev. 3. Rome, Italy: The Food and Agriculture Organization. https://www.fecpl.ca/wp-content/uploads/2018/07/ca0388en.pdf

Drimie, S., & McLachlan, M. (2013). Food security in South Africa—first steps toward a transdisciplinary approach. *Food Security, 5,* 217-226.

Du Preez, H. H., Heath, R. G. M., Sandham, L. A., & Genthe, B. (2003). Methodology for the assessment of human health risks associated with the consumption of chemical contaminated freshwater fish in South Africa. *Water SA, 29***,** 69–90.

Ellender, B. R., Weyl, O. L. F., & Winker, H. (2009). Who uses the fishery resources in South Africa's largest impoundment? Characterising subsistence and recreational fishing sectors on Lake Gariep. *Water SA* 35**,** 677-684.

Esua, O. J., Cheng, J.-H., & Sun, D.-W. (2020). Antimicrobial activities of plasma-functionalized liquids against foodborne pathogens on grass carp (C*tenopharyngodon idella*). *Applied Microbiology and Biotechnology, 104,* 9581–9594. https://doi.org/10.1007/s00253-020-10926-z

Esua, O. J., Cheng, J.-H., & Sun, D.-W. (2021) Functionalization of water as a nonthermal approach for ensuring safety and quality of meat and seafood products. *Critical Reviews in Food Science and Nutrition, 61*(3), 431-449. https://doi.org/10.1080/10408398.2020.1735297

Failler, P., Beyens, Y., & Asiedu, B. (2014). Value chain analysis of the fishery sector in Ghana with focus on quality, environmental, social, sustainable, food safety, organic requirements and its compliance infrastructure.US/GHA/06/005 - Contract No. 3000018889. Trade Capacity Building Programme for Ghana, INDO/MOTI TCB Project.

https://www.academia.edu/17998455/Value_chain_analysis_of_the_fishery_sector_in_Ghana_with_focus_on_quality_environmental_social_sustainable_food_safety_organic_requirements_and_its_compliance_infrastructure

FAO. (1997). Inland Fisheries. In: FAO Fisheries and Aquaculture Department, Food and Agriculture Organization, Rome, Italy. Retrieved from http://www.fao.org/inland-fisheries/background/about-inland-fish/en/ .

FAO. (2016). The state of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all. Rome. 200 pp. Retrieved from https://doi.org/10.18356/8e4e0ebf-en

FAO. (2018). The State of World Fisheries and Aquaculture 2018. Meeting the sustainable development goals. In: FAO Rome, Italy. Retrieved from https://www.fao.org/documents/card/en/c/I9540EN/

FAO. (2019). *FAO yearbook. Fishery and Aquaculture Statistics 2017/FAO annuaire. Statistiques des pêches et de l'aquaculture 2017/FAO anuario.* Estadísticas de pesca y acuicultura 2017. Rome.

FAO, IFAD, UNICEF, WFP and WHO. (2020). The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Rome, FAO. https://doi.org/10.4060/ca9692en

Fridman, D., Friedman, G., Gutsol, A., Shekhter, A. B., Vasilets, V. N., & Fridman, A. (2008). Applied plasma medicine. *Plasma Processes and Polymers 5*, 503– 533.

Funge-Smith, S., & Bennett, A. (2019). A fresh look at inland fisheries and their role in food security and livelihoods. *Fish and Fisheries, 20*(6), 1176-1195. https://doi.org/10.1111/faf.12403

Genschick, S., Kaminski, A. M., Kefi, A. S., & Cole., S. M. (2017). Aquaculture in Zambia: An overview and evaluation of the sector's responsiveness to the needs of the poor. Penang, Malaysia: CGIAR Research Program on Fish Agri-Food Systems and Lusaka, Zambia: Department of Fisheries. Working Paper: FISH-2017-08.

Genschick, S., Marinda, P., Tembo, G., Kaminski, A. M., & Thilsted, S. H. (2018). Fish consumption in urban Lusaka: The need for aquaculture to improve targeting of the poor. *Aquaculture, 492*, 280-289. https://doi.org/10.1016/j.aquaculture.2018.03.052.

Ghaly A., Dave, D., Budge, S., & Brooks, M., (2010). Fish spoilage mechanism and preservation techniques: Review. *American Journal of Applied Sciences, 7*(7), 859-877.

Giannoglou, M., Stergiou, P., Dimitrakellis, P., Gogolides, E., Stoforos, N., & Katsaros, G. (2020). Effect of cold atmospheric plasma processing on quality and shelf life of ready-to-eat leafy salads. *Innovative Food Science and Emerging Technologies, 66,* 102502. https://doi.org/10.1016/j.ifset.2020.102502

Giron-Nava, A., Lam, V. W. Y., Aburto-Oropeza, O., Cheung, W. W. L., Halpern, B. S., Sumaila, U. R., & Cisneros-Montemayor, A. M. (2020). Sustainable fisheries are essential but not enough to ensure. *Fish and Fisheries, 22,* 812–821. https://doi.org/10.1111/faf.12552

Hammond, S. T., Brown, J. H., Burger, J. R., Flanagan, T. P., Fristoe, T. S., Mercado-Silva, N., Nekola, J. C., & Okie, J. G. (2015). Food spoilage, storage, and transport: Implications for a sustainable future. *BioScience*, *65*(8), 758–768.

Hara, M. M., & Backeberg, G. R. (2014). An institutional approach for developing South African inland freshwater fisheries for improved food security and rural livelihoods. *Water SA*, *40*(2), 277–286.

Heinlin, J., Morfill, G., Landthaler, M., Stolz, W., Isbary, G., Zimmerman, J. L., Shimizu, T., & Karrer S. (2010). Plasma medicine: possible applications in dermatology. *Journal of the German Society of Dermatology 8,* 968– 976. https://doi.org/10.1111/j.1610-0387.2010.07495.x

Herianto, S., Hou, C.-Y., Lin, C.-M., & Chen, H.-L. (2021). Non-thermal plasma-activated water: A comprehensive review of this new tool for enhanced food safety and quality. *Compr Rev Food Science Food Safety, 20*, 583–626. https://doi.org/10.1111/1541-4337.12667

Jeffries, D. J., Akande, G. R., & Ward, A. R. (2000). Loss Assessment Using Intervention Load Tracking; DFID PHFRP: London, UK.

Joardder, M. U. H., & Masud, M. H. (2019). Food preservation in developing countries: Challenges and solutions. In M. U. H.,Joardder, & M. H. Masud Eds.), *Food Preservation in Developing Countries: Challenges and Solutions*. (pp 67-125). Springer. https://doi.org/10.1007/978-3-030-11530-2

Kaminski, A. M., Little, D. C., Middleton, L., Syapwaya, M., Lundeba, M., Johnson, J., Huchzermeyer, C., & Thilstead, S. H. (2021). The role of aquaculture and capture fisheries in meeting food and nutrition security: Testing a nutrition-sensitive pond polyculture intervention in rural Zambia. *Foods, 11*, 1334. https://doi.org/10.3390/foods11091334

Kaminski, A. M., Cole, S. M., Al Haddad, R. E., Kefi, A. S., Chilal, A. D., Chisule, G., Mukuka, K. N., Longley, C., Teoh, S. J., & Ward, A. R. (2020). Fish losses for whom? A gendered assessment of post-harvest losses in the Barotse Floodplain Fishery, Zambia. *Sustainability, 12,* 10091. Https:// doi:10.3390/su122310091

Katsaros, G., Koseki, S., Ding, T., & Valdramidis, V. P. (2021). Application of innovative technologies to produce activated safe ice. *Current Opinions in Food Science, 38,* 198–203.

Kawarazuka, N., & Béné, C. (2010). Linking small-scale fisheries and aquaculture to household nutritional security: an overview. *Food Security, 2*, 343–357.

Kawarazuka, N., & Béné, C. (2011). The potential role of small fish species in improving micronutrient deficiencies in developing countries: Building evidence. *Public Health Nutrition, 14,* 1927–1938. https://doi.org/10.1017/S1368980011000814.

Kent, G. (1997). Fisheries, food security, and the poor. *Food Policy, 22* (5), 393-404.

Kumar, A, Skoro, N., Gernjak, W. & Puac, N. (2021). Cold atmospheric plasma technology for removal of organic micropollutants from wastewater – a review. *European Physical Journal D, 75*, 283-309.

Kumolu-Johnson, C. A., Aladetohun, N. F., & Ndimele, P. E. (2010). The effects of smoking on the nutritional qualities and shelf-life of *Clarias gariepinus* (Burchell, 1822). *African Journal of Biotechnology*, *9*(1), 73-76.

Lackmann, J. -W., & Bandow, J. E. (2014). Inactivation of microbes and macromolecules by atmospheric-pressure plasma jets. *Applied Microbiology Biotechnology, 98,* 6205–6213.

Liao, X., Su, Y., Liu, D., Chen, S., Hu, Y., Ye, X., Wang, J., & Ding, T. (2018). Application of atmospheric cold plasma-activated water (PAW) ice for preservation of shrimps (*Metapenaeus ensis*). *Food Control, 94,* 307–314.

Lin, T., Wang, J. J., Li, J. B., Liao, C., Pan, Y. J., & Zhao, Y. (2013). Use of acidic electrolyzed water ice for preserving the quality of shrimp. *Journal of Agricultural and Food Chemistry*, *61*(36), 8695–8702. https://doi.org/10.1021/JF4019933

Liu, X., Zhang, M., Meng, X. I., Bai, Y., & Dong, X. (2021). Effect of plasma-activated water on *Shewanella putrefaciens* population growth and quality of yellow river carp (*Cyprinus carpio*) fillets. *Journal of Food Protection, 84*(10):1722-1728. https://doi.org/10.4315/JFP-21-031. PMID: 34047785.

Lynch, A. J., Cooke, S. J., Deines, A., Bower, S., Bunnell, D. B., Cowx, I. G., Nguyen, V. M., Nonher, J., Phouthavong, K., Riley, B., Taylor, W. W., Woelmer, W., Youn, S. J., & Douglas, B. T. (2016). The social, economic, and ecological importance of inland fishes and fisheries. *Environmental Reviews, 24*. https://doi.org/10.1139/er-2015-0064.

Masipa, T. S. (2017). The impact of climate change on food security in South Africa: Current realities and challenges ahead. *Jamba: Journal of Disaster Risk Studies*, *9*(1), 1–7. https://doi.org/10.4102/jamba.v9i1.411

Maulu, S., Hasimuna, O. J., Monde, C., & Mweemba, M. (2020). An assessment of postharvest fish losses and preservation practices in Siavonga district, Southern Zambia. *Fisheries and Aquatic Sciences*, *23*(1), 25. https://doi.org/10.1186/s41240-020-00170-x

McCafferty, J., Ellender, B., Weyl, O., & Britz, P. (2012). The use of water resources for inland fisheries in South Africa: Review. *Water SA*, *38*(2), 327–344. Retrieved from http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1816-79502012000200018&lng=en&nrm=iso&tlng=en

McCafferty, J. R. (2012). An assessment of inland fisheries in South Africa using fisheries-dependent and fisheries independent data sources. Master of Science, Rhodes University.

Mcfadyen, G., Nasr-Alla, A. M., Al-Kenawy, D., Fathi, M., Hebicha, H., Diab, M. H., Hussein, S. M., Abou_zeid, R. M., & El-Naggar, G. (2012). Value-chain analysis

— An assessment methodology to estimate Egyptian aquaculture sector performance. *Aquaculture* 362–363,18–27. https://doi:10.1016/j.aquaculture.2012.05.042.

Méndez, I. M., & Abuin, J. G. (2012). Thermal processing of fishery products. In *Thermal food processing* – New technologies and quality issues (Ed. Sun, D. -W.,) pp 235-256. CRC, Taylor and Francis.

Mgawe, I. Y. (2008). Postharvest fish loss assessment on Lake Victoria sardine fishery in Tanzania-Rastrineobola Argentea. FAO Fisheries and Aquaculture Report No. 904: 85–96.

Mohamed, E. E., Younis, E. R., & Mohamed, E. A. (2021). Impact of atmospheric cold plasma (ACP) on maintaining bolti fish (Tilapia nilotica) freshness and quality criteria during cold storing. *Journal of Food Processing and Preservation*, *45*(5), e15442. https://doi.org/10.1111/jfpp.15442

Muchuru, S., & Nhamo, G. (2018). Climate change adaptation and the African fisheries: evidence from the UNFCCC National Communications. *Environment, Development and Sustainability, 20*(4), 1687-1705. https://doi.org/10.1007/s10668-017-9960-6

Ni, Y., Lynch, M. J., Modic, M., Whalley, R. D., & Walsh, J. L. (2016). A solar powered 141 handheld plasma source for microbial decontamination applications. *Journal Physics D. Applied Physics*, *49*(35), 355203.

Nölle, N., Grenschick, S., Schwadorf, K., Hrenn, H., Brandner, S., & Biesalski, H. K. (2020). Fish as a source of (micro)nutrients to combat hidden hunger in Zambia. *Food Security, 12*, 1385–1406. https://doi.org/10.1007/s12571-020-01060-9

Odoli, C., Oduor-Odote, P. M., Onyango, S. O., & Ohowa, B. (2013). Evaluation of fish handling techniques employed by Artisanal fishers on quality of *Lethrinids* and *Siganids* fish genera at landing time along the Kenyan coast using Sensory and microbiological methods. *African Journal of Food, Agriculture, Nutrition and Development*, *13*(5), 8167–8186.

Oduor-Odote, P. M., Shitanda, D., Obiero, M., & Kituu, M. G. M. (2010a). Drying Characteristics and some quality attributes of *Rastrineobola argentea* (Omena) and *Stolephorus delicatulus* (Kimarawali). *African Journal of Food Agriculture and Nutrition Development, 10*(8), 2998-3006.

Oduor-Odote, P. M., Obiero, M., & Odoli, C. (2010b). Organoleptic effect of using different plant materials on smoking of marine and freshwater catfish. *African Journal of Food Agriculture and Nutrition Development*, *10*(6), 2658-2677. https://doi.org/10.18697/ajfand.76.15900.

Oh, J.-S., Endre, J. S., Nishtha, G., Song, S. -H., Furuta, H., Kurita, H., Mizuno, A., Hatta, A., & Short, R. D. (2016). How to assess the plasma delivery of RONS into tissue fluid and tissue. Journal of Physics D: *Applied Physics 49* (30), 304005. https://doi.org/10.1088/0022-3727/49/30/304005

Olatunde, O. O., Singh, A., Shiekh, K. A., Nuthong, P., & Benjakul, S. (2021a). Effect of high voltage cold plasma on oxidation, physiochemical, and gelling properties of myofibrillar protein isolate from Asian sea bass (*Lates calcarifer*). *Foods, 10*(2), 326. https://doi.org/10.3390/foods10020326

Olatunde, O. O., Tan, S. L. D., Shiekh, K. A., Benjakul, S. & Nirmal, N. P. (2021b). Ethanolic guava leaf extracts with different chlorophyll removal processes: Anti-melanosis, antibacterial properties and the impact on qualities of Pacific white shrimp during refrigerated storage. *Food Chemistry*, 30(341), 11331-11350. https://doi.org/10.1016/j.foodchem.2020.128251.

Onyutha, C. (2019). African food insecurity in a changing climate: The roles of science and policy. *Food & Energy Security, 8*(1), e00160.

Pei, X., Liu, J., Xian, Y., & Lu, X. (2014). A battery-operated atmospheric-pressure plasma wand for biomedical applications. *Journal of Physics D: Applied Physics*, *47*. 145204. https://doi.org/10.1088/0022-3727/47/14/145204.

Perez, S. M., Biondi, E., Laurita, R., Proto, M., Sarti, F., Gherardi, M., Bertaccini, A., & Colombo, V. (2019). Plasma activated water as resistance inducer against bacterial leaf spot of tomato. *PloS One*, *14*(5). https://doi.org/10.1371/journal.pone.0217788

Qu, G. Z., Liang, D. L., Qu, D., Huang, Y. M., Liu, T., Mao, H., Ji, P. H. & Huang, D. L. (2013). Simultaneous removal of cadmium ions and phenol from water solution by pulsed corona discharge plasma combined with activated carbon. *Chemical Engineering Journal, 228*, 28-35.

Sakudo, A., & Yagyu, Y. (2021). Application of a roller conveyor type plasma disinfection device with fungus-contaminated citrus fruits. *AMB Express 11* (16), 1-8. https://doi.org/10.1186/s13568-020-01177-2

Shawyer, M., & Medina Pizzali, A. F. (2003). The use of ice on small fishing vessels. FAO Fisheries Technical Paper. https://www.fao.org/fishery/en/publications/33423

Shiekh, K. A., & Benjakul, S. (2020). Effect of high voltage cold atmospheric plasma processing on the quality and shelf-life of Pacific white shrimp treated with Chamuang leaf extract. *Innovative Food Science & Emerging Technologies, 64,* 102435. https://doi.org/10.1016/j.ifset.2020.102435

Sheng, L., & Wang, L. (2021). The microbial safety of fish and fish products: Recent advances in understanding its significance, contamination sources, and control strategies. *Comprehensive Reviews in Food Science and Food Safety*, *20*(1), 738–786. https://doi.org/10.1111/1541-4337.12671

Siddique, S. S., Hardy, G. E. St. J., & Bayliss, K. L. (2019). Cold plasma as a novel treatment to reduce the *in vitro* growth and germination of *Colletotrichum* species. *Plant Pathology 68*, 1361–1368. https://doi.org/10.1111/ppa.13059

Soni, A., Choi, J., & Brightwell, G. (2021). Plasma-activated water (PAW) as a disinfection technology for bacterial inactivation with a focus on fruit and vegetables. *Foods, 10,* 166. https://doi.org/10.3390/foods10010166

Statistics South Africa. (2008). Income and expenditure of households 2005/2006: Analysis of results. Pretoria: Statistics South Africa. https://www.statssa.gov.za

Tawari, C. C., & Abowei, J. F. N. (2011). Traditional fish handling and preservation in Nigeria. *Asian Journal of Agricultural Sciences, 3*(6), 427-436.

Termeer, C. J. A. M., Drimie, S., Ingram, J., Pereira, L., & Whittingham, M. J. (2018). A diagnostic framework for food system governance arrangements: The case of South Africa. *NJAS-Wageningen Journal of Life Sciences*, *84*, 85–93.

Troell, M., Tyedmers, P., Kautsky, N., & Ro¨nnba¨ck, P. (2004). Aquaculture and energy use. *Encyclopedia of Energy, 1,* 97–108.

UNICEF (2013). National Micronutrient Survey 2011-12, Final Report. Dhaka, Bangladesh: Institute of Public Health Nutrition, United Nation Children's Fund (UNICEF), icddr,b and Global Allaince for Improved Nutrition (GAIN). https://www.unicef.org/bangladesh/media/4631/file/National%20Micronutrient%20Survey%202011-12.pdf.pdf

United Nations (2019). World Population Prospects: The 2019 Revision. New York. Online Edition. Rev. 1. Department of Economic and Social Affairs, Population Division, United Nations. Available from https://population.un.org/wpp/Download/Standard/Population/:

Usta, Y., Çukur, E., Yıldırım, Ç., & Ercan, U. (2019). Design of a portable, battery-powered non-thermal atmospheric plasma device and characterization of its antibacterial efficacies. *Journal of Electrostatics, 99,* 1-8. https://doi.org/10.1016/j.elstat.2019.03.002.

Van Niekerk, W., Le Roux, A., & Pieterse, A. (2019). CSIR launches novel online climate risk profiling and adaptation tool: The Green Book. *South African Journal of Science, 115*. https://doi.org/10.17159/sajs.2019/6238.

Wang, Q., & Salvi, D. (2021). Recent progress in the application of plasma-activated water (PAW) for food decontamination. *Current Opinion in Food Science, 41,* 51–60.

Wang, J., Fu, T., Sang, X. & Liu, Y. (2022). Effects of high voltage atmospheric cold plasma treatment on microbial diversity of tilapia (*Oreochromis mossambicus*) fillets treated during refrigeration. *International Journal of Food Microbiology 375*, 109378

Ward, A. R., & Jeffries, D. J. (2000). A Manual for Assessing Post-Harvest Fisheries Losses; Natural Resources Institute (NRI): Chatam, UK.

Welcomme, R. L., Cowx, I. G., Coates, D., Béné, C., Funge-Smith, S., Halls, A., & Lorenzen, K. (2010). Inland capture fisheries. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1554), 2881-2896. https://doi.org/10.1098/rstb.2010.0168

Weyl, O. L. F., Barkhuizen, L., Christison, K., Dalu, T., Hlungwani, H. A., Impson, D., Sankar, K., Mandrak, N. E., Marr, S. M., Sara, J. R., Smit, N. J., Tweddle, D., Vine, N. G., Wepener, V., Zvavahera, M., & Cowx, I. G. (2021). Ten research questions to support South Africa's Inland Fisheries Policy. *African Journal of Aquatic Science, 46*(1), 1-10. https://doi:10.2989/16085914.2020.1822774

World Bank. (2021). South Africa. Retrieved 8 July – 8 August, 2021, from https://data.worldbank.org/country/ZA

Xiang, Q., Fan, L., Li, Y., Dong, S., Li, K., & Bai, Y. (2020). A review on recent advances in plasma-activated water for food safety: current applications and future trends. *Critical Reviews in Food Science and Nutrition*, 1-20. https://doi.org/10.1080/10408398.2020.1852173

Xu, D. H., Cui, Q. J.., Xu, Y J., Liu, D. X., Kong, G. Y. (2017). Plasma medicine and the application in tumor therapy. *Progress in Biochemistry and Biophysics, 44,* 279–92.

Xuan, X. T., Fan, Y. F., Ling, J. G., Hu, Y. Q., Liu, D. H., Chen, S. G., Ye, X. Q., & Ding, T. (2017). Preservation of squid by slightly acidic electrolyzed water ice. *Food Control*, *73*, 1483–1489. https://doi.org/10.1016/J.FOODCONT.2016.11.013

Youn, S. J., Taylor, W. W., Lynch, A. J., Cowx, I. G., Douglas Beard, T., Bartley, D., & Wu, F. (2014). Inland capture fishery contributions to global food security and threats to their future. *Global Food Security*, *3*(3–4), 142–148. https://doi.org/10.1016/J.GFS.2014.09.005

Zeltmann, K. -D., & von Woedtke, T. (2017) Plasma medicine—current state of research and medical application. *Plasma Physics and Controlled Fusion, 59*(1), 014031. https://doi.org/10.1088/0741-3335/59/1/014031

Zhang, H., Ma, D., Qiu, R., Tang, Y. & Du, C. (2017) Non-thermal plasma technology for organic contaminated soil remediation: A review. *Chemical Engineering Journal, 313*, 157-170.

Zhao, Y. M., Ojha, S., Burgess, C. M., Sun, D., & Tiwari, B. K. (2020). Influence of various fish constituents on inactivation efficacy of plasma-activated water. *International Journal of Food Science & Technology*, *55*(6), 2630–2641.

Zhao, Y. M., Oliveira, M., Burgess, C. M., Cropotova, J., Rustad, T., Sun, D. W., & Tiwari, B. K. (2021). Combined effects of ultrasound, plasma-activated water, and peracetic acid on decontamination of mackerel fillets. *LWT*, *150,* 111957. https://doi.org/10.1016/j.lwt.2021.111957

Zhou, R., Zhou, R., Prasad, K., Fang, Z., Speight, R., Bazaka, K., & Ostrikov, K. K. (2018). Cold atmospheric plasma activated water as a prospective disinfectant: The crucial role of peroxynitrite. *Green Chemistry*, *20*(23), 5276–5284. https://doi.org/10.1039/C8GC02800A

Zhou, R., Zhou, R., Wang, P., Xian, Y., Mai-Prochnow, A., Lu, X., Cullen, P., Ostrikov, K. K., & Bazaka, K. (2020). Plasma-activated water: Generation, origin of reactive species and biological applications. *Journal Physics D: Applied Physics, 53,* 303001. https://doi.org/10.1088/1361-6463/ab81cf