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RESEARCH

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Histological features of the gastrointestinal tract of elongate tigerfish, *Hydrocynus forskahlii* (Cuvier, 1819), from Lake Albert

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Abstract

Background The tigerfish (*Hydrocynus forskahlii*) is an important food fish in different regions of Africa. As such, interest in its performance and nutritional requirements as a potential candidate for aquaculture is increasing. Characterization of the morpho-histological features and functions of the gut provides valuable insights into the feeding physiology and digestive system of fish species.

Result An investigation of the morpho-histological features of the gastrointestinal tract of *H. forskahlii* captured from Lake Albert was conducted over an eight-month period. The digestive tract of *H. forskahlii* is characterised by a short oesophagus, well-developed and distensible stomach and moderately long intestine. The oesophagus had a higher abundance of mucous-secreting goblet cells compared to other digestive tract tissues. The stomach had a bag-like shape for swallowing large prey and was distinguishable into the cardiac, fundic and pyloric regions. Both the cardiac and fundic regions of the stomach had numerous gastric glands, whereas the pyloric region had large compound folds consisting of pseudo-stratified columnar epithelium. Many goblet cells were also observed in the mid and posterior regions of the intestine. The relative length of the gut of the *H. forskahlii* was 1.27 ± 0.03 cm, and it had a total of 20–22 pyloric caeca. The liver was observed to be divided in lobules by a central vein contained within connective sheets. Irregular cords of hepatocytes were also visible throughout the parenchyma.

Conclusions The histological features of the *H. forskahlii* gut observed in the present study are consistent with those of carnivorous and omnivorous fish.

Keywords Elongate tigerfish, Digestive tract, Digestive physiology, Lake Albert

Background

The characterization of the histo-morphological features and function of the gastrointestinal tract of fish is important in determining the taxonomy and feeding habits (Murray et al., 1996). Fishes feed on different natural feeds that are distributed at varying water depths. Their feeding behaviour and nature of their digestive tract provide useful ecological and biological information (Cho et al., 2023). Fishes are widely classified into carnivores, herbivores and omnivores based on their feeding habits (De Silva & Anderson, 1995; Rust, 2002). The morphology of the digestive apparatus is an adaptation to their food and feeding habits. As in other vertebrates, the digestive system comprises of the alimentary canal and associated

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organs. The alimentary canal, which varies in diameter, consists of the oesophagus, stomach, intestine, rectum and anus (Pena et al., 2003). Its major associated organs include the tongue, teeth, liver, gall bladder and pancreas (Alabssawy et al., 2019; Kasozi et al., 2017). Histological research on the internal structure and morphology of the digestive system is crucial for improving our understanding of the food and digestive physiology of fish. As such, they are becoming more common for insights supporting the development of appropriate feeds and feeding strategies for emerging fish species for aquaculture.

There are six fish species in the genus *Hydrocynus,* all of which are endemic to Africa (Goodier et al., 2011; Roux et al., 2018). With regard to ecological and economic significance, tigerfishes are widely distributed in the majority of large African river systems and rank highly as one most important freshwater predatory fish (Jackson, 1961; Lewis, 1974). The elongate tigerfish, *H. forskahlii*, is a member of the family Alestidae. It is a potamodromous and pelagic predator, widely distributed in different parts of Africa (Akinyi et al., 2020; Fig. 1). In Uganda, the fish is endangered and found in Lake Albert and parts of the Albert Nile (Mbabazi et al., 2012; Nakiyende et al., 2013; Kasozi et al., 2013; Akinyi et al., 2020). Up until the early 2000s, *H. forskahlii* was a significant commercial species harvested in Lake Albert. However, evidence from catch assessment survey data (2007–2013) shows a decline in commercial harvests from 72.7% in 1971 to less than 6% in 2013, attributed to high exploitation pressure (Nakiyende et al., 2013).

Fig. 1 Distribution map for *H. forskahlii* in Africa. Adapted from Akinyi et al. (2020). Extant (Resident), presence uncertain

While the interest in understanding more about the anatomy and histology of fish digestive systems is on the increase, investigations for species in the Alestidae family are scarce. Studies in this family have focused more on *Alestes baremoze* than other species in the same family (Kasozi et al., 2017, 2019). Thus, this study aimed at describing the histological characteristics of the gastrointestinal tract of *H. forskahlii* collected from Lake Albert. This could serve as a baseline for comparative studies on digestion, absorption and feeding behaviour in future.

Methods

Sample collection

A total of 55 apparently healthy adult *H. forskahlii* specimens consisting of 10 males and 45 females were caught using gill nets of 4 inches from Lake Albert in Uganda between October 2022 and May 2023. The mean (± standard deviation) of wet body mass and total length of the 55 samples of *H. forskahlii* were 1094.36 ± 255.76 g and 40.84 ± 2.19 cm, respectively. The specimens were immediately placed in coolboxes containing ice and transported to the laboratory where they were cleaned. For each fish, a ventral incision was made from the anus to the mouth to expose the digestive system. The individual organs were examined *in situ*, dissected and captured using a digital camera. The relative length of gut (RLG) was determined according to the following formula described by Kasozi et al. (2017).

$$\text{RLG} = \text{Absolute gut length (cm)}/\text{standard body length (cm)}$$

Histological description

Four small tissue sections from the esophagus, stomach, intestine, pyloric caeca and liver were instantly fixed by immersion in Bouin's solution. Tissue sections were prepared following standard histological procedures and were stained using both haematoxylin and eosin (H&E) and Masson's trichrome staining protocol as described by Bancroft & Gamble (2008). The stained sections were visualized using a light microscope (Carl Zeiss, Germany). The length, thickness, presence of folds and sphincters in the digestive organs were all taken into consideration for histological descriptions. Consideration was given to the structure of the mucosal epithelia, type of cell, presence of glands and the organisation of the tunica muscularis and tunica serosa.

Results

Gross morphological description

Elongate tigerfish, *H. forskahlii*, has a golden-green coloured head darkening towards the dorsal part of the head. The wide mouth contained strong bony cheeks and muscular jaws. The fish had nine protruding sharp pointed teeth in the upper jaw and eight in lower jaw (Fig. 2). They have a fusiform body, deeply forked caudal fin, yellow to blood red tinted dorsal, pectoral and pelvic fins with black trailing edges and prominent black stripes (Fig. 2). They have big scales, with 44–48 on the lateral line and 15–16 in the area surrounding the caudal peduncle. According to macroscopic observations, *H. forskahlii* has a large but short tubular oesophagus that extends from the back of the pharynx to the stomach's anterior cardiac area.

The relative length of gut of the fish collected during the study ranged from 1.23 to 1.35 cm with an average of 1.27 ± 0.03 cm. The stomach is sac-like and extended from the oesophagus to anterior intestine. It has three distinct regions, i.e. cardiac, fundic, and pyloric (Fig. 3). The pyloric region is the terminal part of the stomach that joins the anterior/proximal part of the intestinal tube. The pyloric caeca are present at the point of convergence of the stomach and intestine (Fig. 3). The intestine was also divided into the anterior, middle and posterior parts as shown in Fig. 3.

Histological features

Oesophagus

The oesophagus of *H. forskahlii* is short and thick with longitudinal folds, which enables the passage of large food items. It consists of a stratified secretory epithelium that lines the oesophageal mucosal layer which lubricates the luminal surface and protects it from abrasion caused by food passage. Towards the posterior part, the number of goblet cells gradually decreases (Fig. 4). Both the inner circular muscle and outer longitudinal muscle of the tunica muscularis were organised in two layers with decreasing thickness gradually towards the posterior end of the oesophagus. The entire length of the oesophagus was covered in tubular glands that were part of the lamina propria. A thin layer of pavement epithelium makes up the serosa layer (Fig. 4).

Stomach

Cardiac stomach

The distensible, sac-like and large stomach of *H. forskahlii* was divided into three regions cardiac (anterior), fundic (middle) and pyloric (posterior). Each of the examined sections of the regions of the stomach showed concentrically arranged folds, namely the mucosa, muscularis and the serosa. The mucosal layer consisted of numerous gastric glands (Fig. 5), whereas the thin layer of submucosa was made up of fibrous connective tissue filled with blood vessels and fibrocytes.

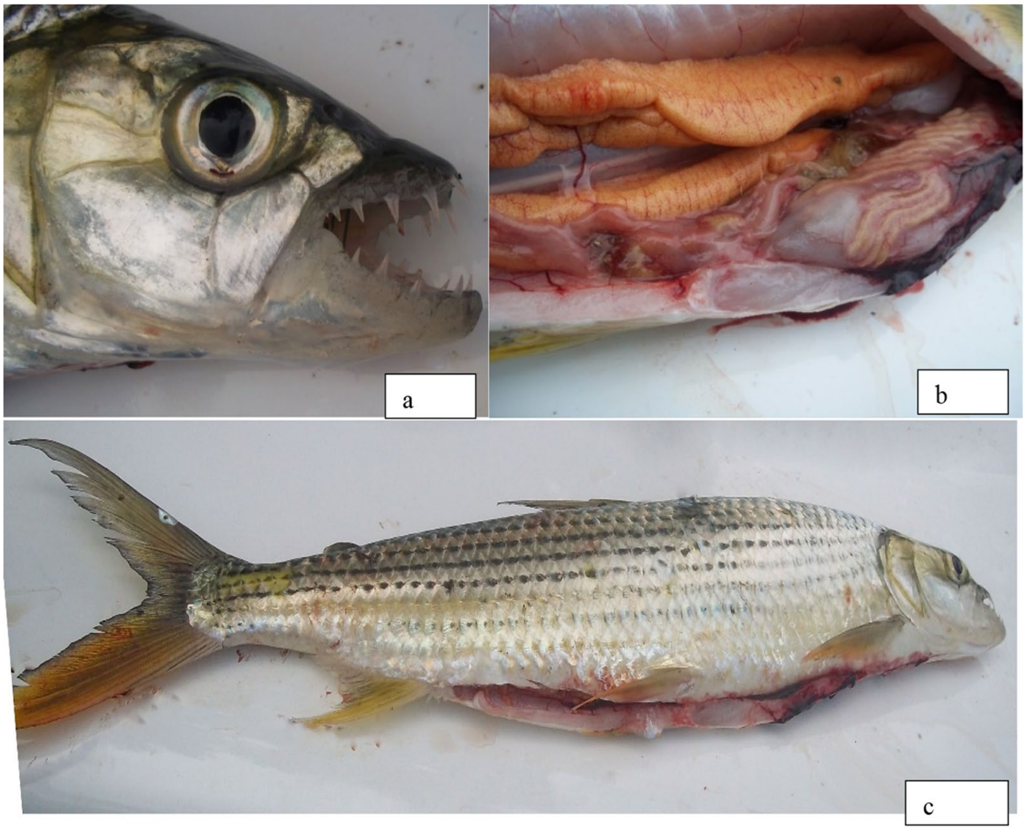

Fig. 2 Gross dissection of the elongate tigerfish *Hydrocynus forskahlii* showing **a** bony cheeks and sharply pointed teeth, **b** contents of body cavity including the GIT and associated organs and **c** lateral view of the external features of the dissected fish. *Scale bar* 50 mm

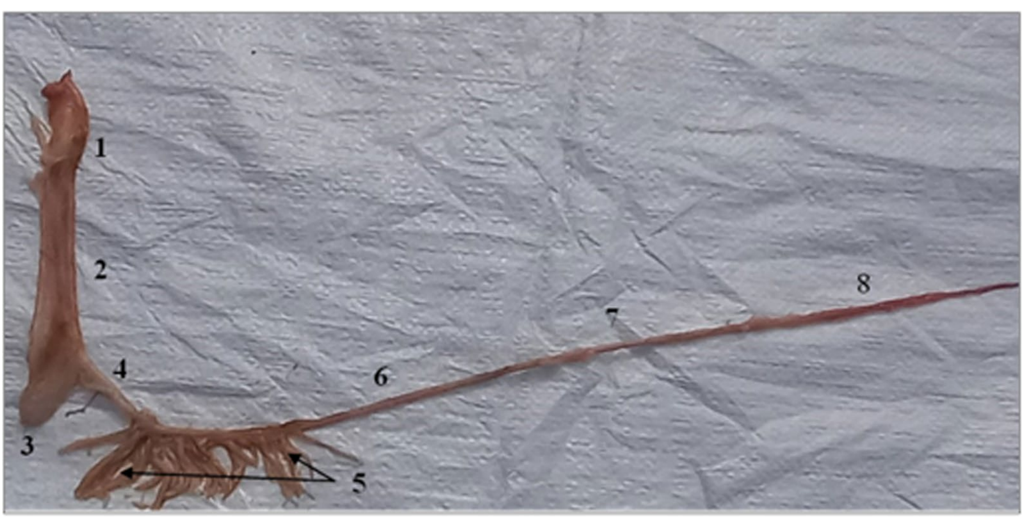

Fig. 3 Structure of the digestive tract of *H. forskahlii* outside the body cavity showing the oesophagus and divisions of the stomach and intestine: (1) oesophagus, (2) cardiac region of the stomach, (3) fundic region of the stomach, (4) pyloric region of the stomach, (5) pyloric caeca, (6) anterior intestine, (7) mid-intestine and (8) posterior intestine. *Scale bar* 50 mm

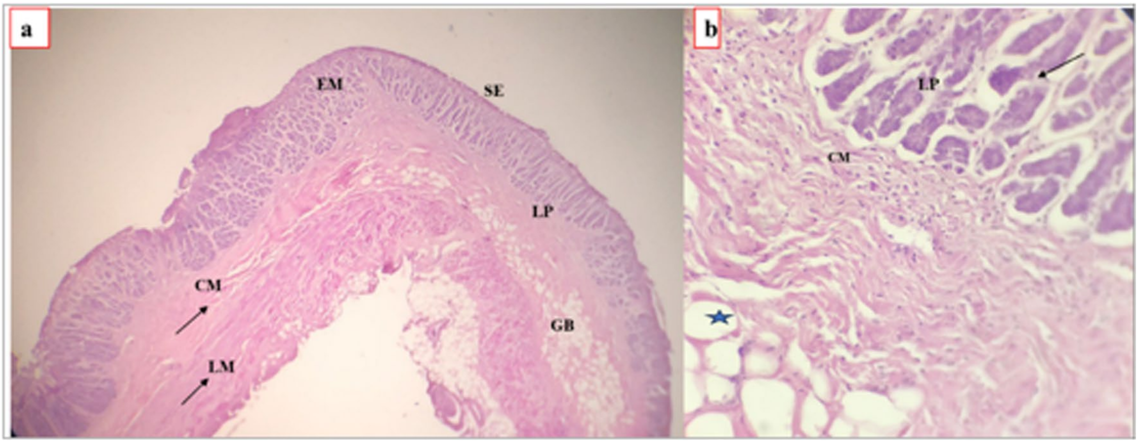

Fig. 4 **a** Histological sections of the oesophagus showing **a** oesophageal mucosa (EM), lamina propria (LP), serosa (SE), presence of Goblet cells (GB) interspersed between the longitudinal muscles (LM) and inner circular muscle (CM) at magnification is ×40. **b** Shows circular muscles (CM), Goblet cells with asterisk. Magnification ×200. Arrow: tubular glands

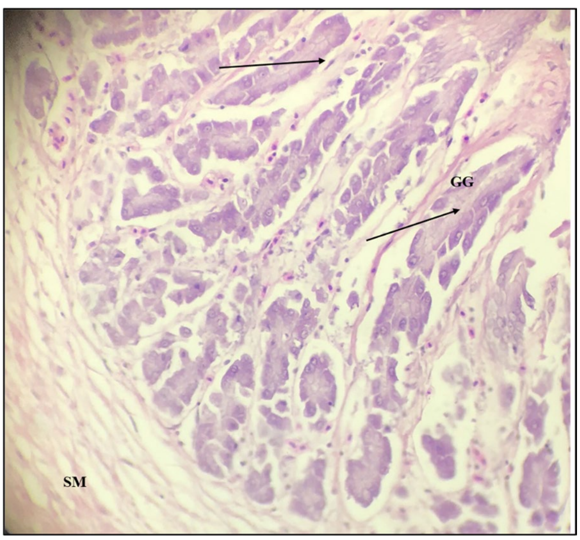

Fig. 5 A transverse histological section of the cardiac stomach showing the groups of gastric glands (GG) and submucosa (SM) consisting of fibrous connective tissue. Magnification ×100

Fundic stomach
The epithelial mucosa possessed groups of gastric glands rounded with basally located nuclei and columnar epithelium (Fig. 6). The thin submucosa consisted of fibrous connective tissue filled with blood vessels and fibrocytes. Under the muscularis, there existed a single layer of squamous cells making up the serosa.

Pyloric stomach
The pyloric and cardiac regions of the stomach lacked a distinct separation. Large compound folds consisting of pseudo-stratified columnar epithelium formed the mucosa (Fig. 7). The lumen is wide at the proximal end of the cardiac region gradually tightening towards the pyloric orifice. The muscularis consisted of an inner circular and outer longitudinal, both of which are unstriated, and is relatively thick (Fig. 7).

Pyloric caeca
A total of 20–22 finger-like pyloric caeca were observed at the point where the stomach and intestine converge. The serosae of the pyloric caeca were observed to be so thin, making it difficult to differentiate them. An inner circular and outer longitudinal layer of smooth muscles formed the tunica muscularis (Fig. 8).

The intestine
Anterior intestine
In the anterior intestine, the mucosal folds were very long, numerous and roughly parallel. Additionally, they had round tips facing lumen (Fig. 9). The thick muscularis was relatively comprised of an inner circular and outer longitudinal muscle layer, both of which were unstriated.

Mid-intestine
There was no distinction between the mid and posterior intestines except for some histological characteristics. It consisted of primary mucosal folds and a comparatively thin submucosa. The epithelial mucosa comprised of a high number of mucus-secreting spherical goblet cells (Fig. 10). The lamina propria was observed to have compact connective tissues consisting of numerous blood vessels that were more abundant at the tip of the villi.

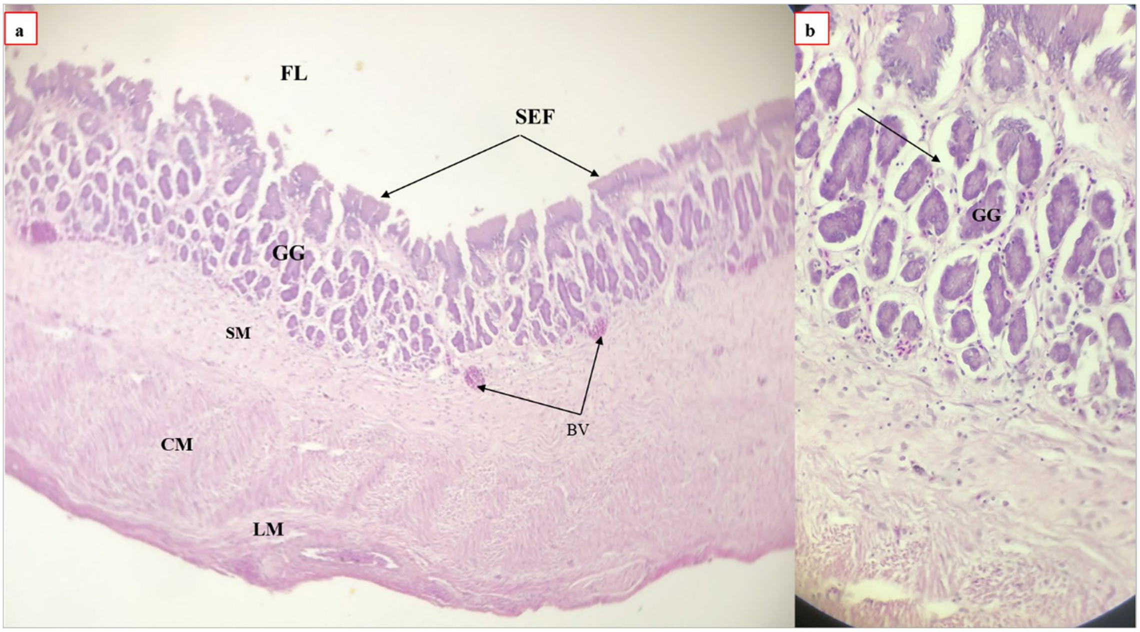

Fig. 6 Histological showing the middle (fundic) region of the stomach at different magnifications; (a) shows the fundic lumen of the stomach (FL), simple columnar epithelium (SEF), blood vessels (BV), gastric glands (GG), submucosa (SM), circular muscle layer (CM) and longitudinal muscle (LM) at magnification ×100 **(a)**. **b** Shows gastric glands (GG) at magnification ×200

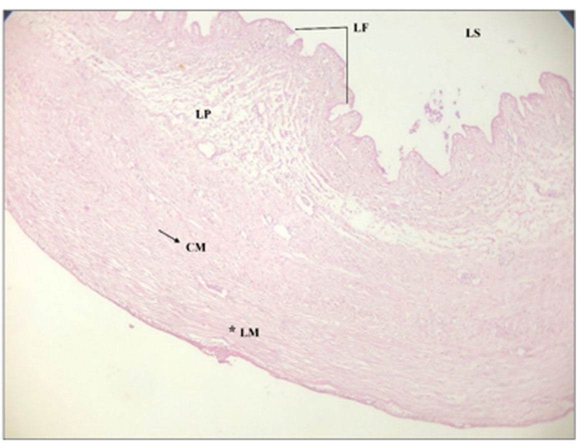

Fig. 7 A transverse histological section of the pyloric region of the *H. forskahlii* stomach showing lumen of the pylorus (LS), pyloric folds in the stomach mucosa (LF), lamina propria (LP), inner circular muscle (CM) and outer longitudinal muscle of the stomach (LM) at magnification of ×100

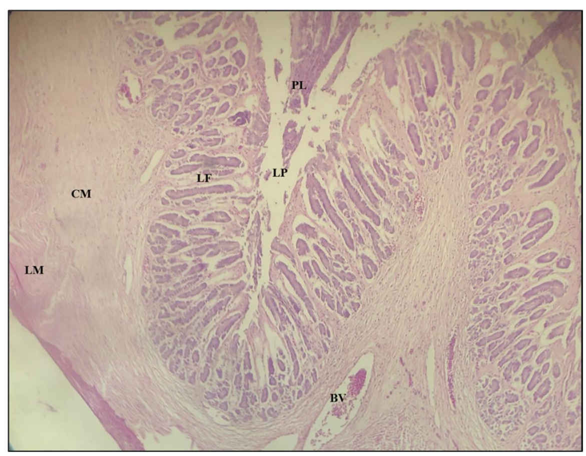

Fig. 8 A transverse histological section of the pyloric caeca showing the lumen (PL), lamina propria (LP), blood vessel (BV), pyloric caeca with mucosa containing numerous folds (LF), stomach inner circular muscle (CM) and outer longitudinal muscle (LM) at magnification ×40

Posterior intestine

The posterior intestine is well-developed, with distinct divisions. The mucosal folds were branched and irregular unlike those in the mid-intestine (Fig. 11). The muscularis externa was thick with long mucosal folds in comparison with those in the pyloric caeca.

Liver

The liver was observed to have a central vein contained within connective tissue sheets. Thus, it was divided into lobules (Fig. 12). Irregular cords of hepatocytes were visible throughout the liver parenchyma. The exocrine pancreas' tubular acinar glands, which make up the hepatopancreas and secretory vesicles, were dispersed throughout the liver lobules (Fig. 12).

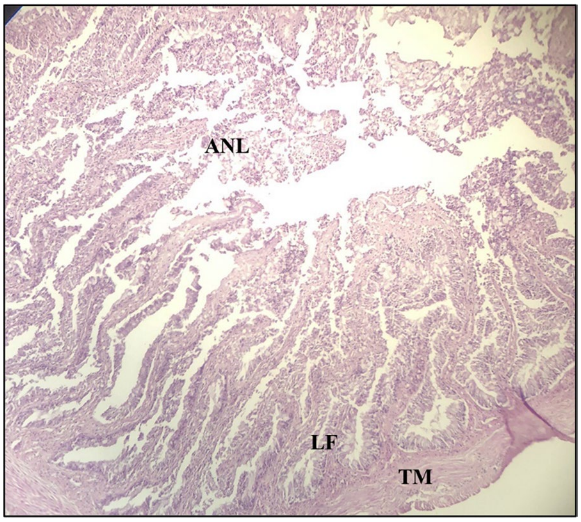

Fig. 9 Histological sections of the anterior region of the intestine showing the lumen filled with food (ANL), longitudinal folds (LF) and tunica muscularis (TM) at magnifications ×100

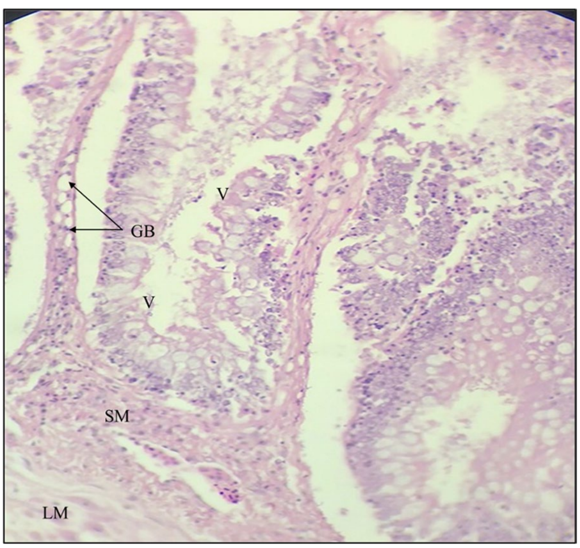

Fig. 10 A transverse histological section of the mid-sections of the intestine of *H. forskahlii* showing the presence of many goblet cells (GB), villi (V), submucosa (SM) and the longitudinal muscles (LM) at magnification ×200

Discussion

The gross morphological analyses conducted in this study showed that the digestive system of the adult *H. forskahlii* has several key features. Most notably, it has sharply pointed teeth, an oesophagus with a well-developed musculature, an extendable saccular stomach, pyloric caeca and slightly long intestine. The relative length of the gut (RLG) is generally used to differentiate the dietary patterns of fish (De & Datta, 1990). The RLG value of adult *H. forskahlii* reported in the present study of 1.27 ± 0.03 cm is closer to the range of RLG values reported for omnivorous (1.3–4.3) fish compared to that reported for carnivorous (0.5–2.4) fish (Al-Hussaini, 1949; Dasgupta, 2004). However, the digestive tract's morphology such as the conical dentition resembled that of carnivorous fish (Kasozi et al., 2017). Dadebo & Mengistou (2008) reported that *H. forskahlii* in Lake Chamo feeds on a variety of food items including zooplankton, insects, macrophytes and fish. Adult tigerfish appear to be mostly opportunistic predators that adapt their diet to suit the available prey as reported by Gagiano (1997).

It was observed that the oesophagus of the *H. forskahlii* was a short muscular distensible and dilated tube. The oesophagus showed a branched form with a stratified secretory epithelial layer of goblet cells. This structure suggests that the oesophagus of the *H. forskahlii* can be enlarged to accommodate food digestion and transportation. Goblet cells were more prevalent in the oesophagus than other digestive system tissues. Mucus is secreted by goblet cells to shield the mucosal epithelial layer, make food substances easier to transport and aid in excretion into the digestive tract (Alabssawy et al., 2019). In this regard, comparable findings were made by previous authors in omnivorous fish, *Alestes baremoze* (Kasozi et al., 2017), piscivorous fish, *Synodus variegatus* (Alabssawy et al., 2019), carnivorous fish, *Anguilla bicolor bicolor* (Nasruddin et al., 2014).

The findings of this study clearly show that *H. forskahlii* has a pouch-like stomach which has been linked to large feed intake and slow digestion by chemicals secreted from the tubular glands (Kasozi et al., 2017). Histologically, the stomach's cardiac and fundic regions consisted of a large number of gastric glands that are crucial for the digestion of food. A very thick layer of muscularis covers the pyloric region, which helps to regulate how quickly the food is passed from the stomach to the intestine. Similar observations have been reported by Alabssawy et al. (2019) for the stomach of piscivorous fish, *Synodus variegatus,* and Kasozi et al. (2017) for *Alestes baremoze*. The presence of gastric glands in the fundic stomach indicates maximum secretion of digestive juices that hydrolyse the diet of *H. forskahlii*.

Fish have developed pyloric caeca as a means of increasing their surface area and, consequently, their capacity to absorb nutrients (Buddington & Diamond, 1986; Canan et al., 2012; Kasozi et al., 2017). Pyloric caeca are also assumed to be major sites of sugar, amino acid and dipeptide uptake (Buddington & Diamond, 1986). A pyloric caecum has evolved in some species with highly developed swimming abilities (such migratory fish) to give high energy to continue swimming (Sano et al., 2021). In the present study, the elongate tigerfish was

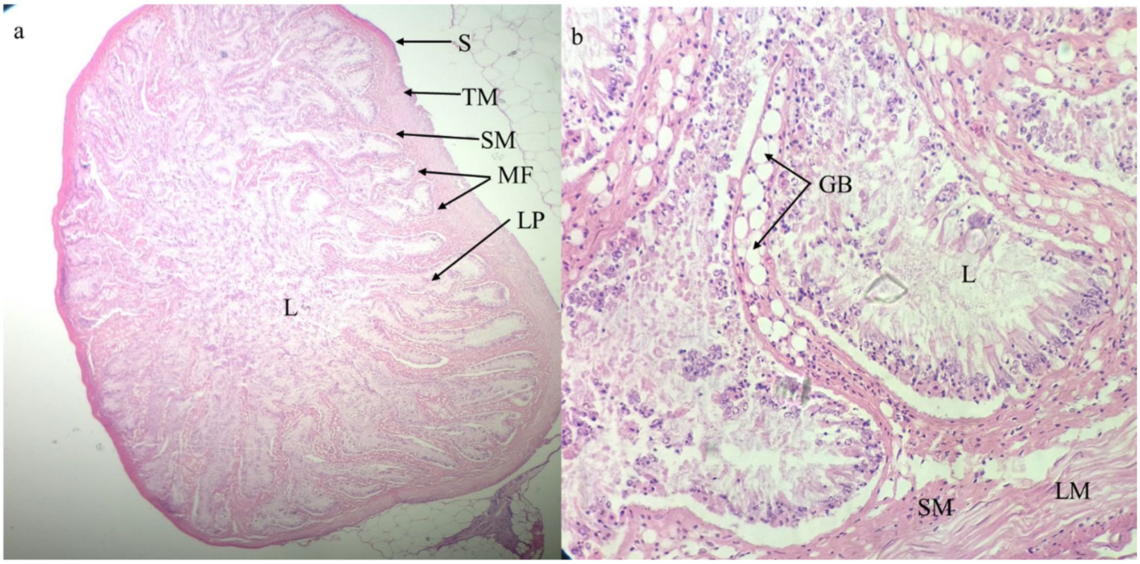

Fig. 11 A transverse histological sections of the posterior intestine in an adult elongate tigerfish showing; **a** the tunics, note the lumen (L) is filled with may debris and cells, serosa (S), tunica muscularis (TM), submucosa (SM), lamina propria (LP), mucosal folds (LF). Magnification ×100. **b** Shows presence of many goblet cells (GB) lining the longitudinal folds (LF), lamina propria (LP), submucosa (SM) and the longitudinal muscles (LM), magnification ×400

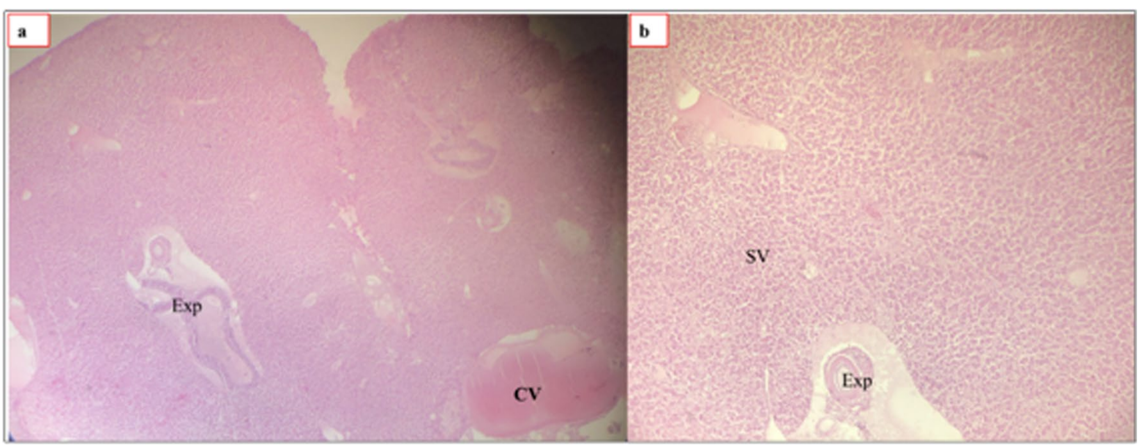

Fig. 12 A transverse histological sections of the liver: **a** central vein (CV), exocrine pancreas (Exp), **b** exocrine pancreas (Exp) with secretory vesicles (SV)

found to have between 20 and 22 pyloric caeca implying that the *H. forskahlii* exhibit migratory tendencies, which is indeed a characteristic of the species. However, more research is needed to establish or further investigate the relationship between the number of pyloric caeca and digestive physiology.

The intestine of *H. forskahlii* is moderately long and thin with more elaborate and complex folds in comparison with those found in the oesophagus or stomach. Cho et al. (2023) reported that the mucosal folds of the fish intestine could improve digestion function and absorption of nutrients. Similar branched patterns could be seen in the mucosal folds of the intestines of *H. forskahlii*; however, the mucosal folds became shorter towards the distal end. This implies that the anterior gut has more digestive functions than the posterior intestine.

In contrast to the other intestinal regions, the posterior intestine of *H. forskahlii* is well-developed, with clear sub-divisions and irregular and complex-shaped mucosal folds. It is assumed that strong muscle contraction at the rectal area is necessary for carnivorous fish to defecate (Nasruddin et al., 2014). As the muscularis externa have been reported to cause propulsive contractions, it is likely that remarkable tunica muscularis observed at the posterior part of the intestine of the *H. forskahlii* perform the same function. This study further revealed the presence of many goblet cells in the mid and posterior intestine of *H. forskahlii* has as reported by Alabssawy et al. (2019) in piscivorous fish, *Synodus variegatus* for faecal lubrication.

Conclusions

This present study characterized the morpho-histological features and functions of the digestive tract of *H. forskahlii* which are similar to both carnivorous and omnivorous fish. Considering the economic and biological importance of this species, findings can support further research to better understand nutritional, pathological and physiological aspects of the species. Further investigations are needed to determine the potential food sources and their contributions to the diet of different sizes of *H. forskahlii*.

Abbreviations

cm	Centimetre
BV	Blood vessels
CM	Circular muscle layer
CV	Central vein
Exp	Exocrine pancreas
FL	Fundic lumen of the stomach
GB	Goblet cells
GG	Gastric glands
GIT	Gastrointestinal tract
H&E	Haematoxylin and Eosin
LF	Pyloric folds in the stomach mucosa
LM	Longitudinal muscle
LP	Lamina propria
LS	Lumen of the pylorus
RLG	Relative length of gut
SEF	Simple columnar epithelium
SE	Serosa
SM	Submucosa
SV	Secretory vesicles
TG	Tubular glands
TM	Tunica muscularis

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Author contributions

NK helped in conceptualisation; methodology; and writing of original draft, GDI collected the data, SL was involved in writing—review and editing, VTN helped in methodology, writing—review and editing, JW contributed to supervision, funding, writing—review and editing. The authors have all read and approved the final manuscript for publication.

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Availability of data and materials

All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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