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Morphological, Histological and Histochemical Adaptations in Digestive Tubular Part, Concerning the Feeding Strategy of Skipjack Tuna (*Katsuwonus pelamis*) Inhabiting Abu Galum, Aqaba Gulf, Red Sea, Egypt

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ABSTRACT

This work aimed to describe the morphological, histological, and histochemical adaptations in the tubular part of the digestive tube of skipjack tuna (*Katsuwonus pelamis*) according to its feeding and dietary preferences. Fish samples were gathered from Abu Galum, Aqaba Gulf, the Red Sea, Egypt, in May 2022. The morphological, histological, and histochemical structure of the oesophagus, stomach, and intestine of fish were photographed and described. The results showed that the esophagus of *K. pelamis* was described as a flexible tube with irregular mucosal folds, comprising multiple layers of mucus cells containing strong acid mucopolysaccharides (MPS) and weak sulphomucins. Submucosa consisted of fibrous connective tissue with variations in mesh size, and the muscularis layer was dense with circular muscle fibers. The stomach has a bag shape. It is separated into three regions cardiac, fundic, and pyloric. The cardiac region exhibited broad folds with dense stomach glands containing weakly acid MPS and sulphomucins. Its submucosa contained blood vessels dispersed in fibrous connective tissue, while the muscular layer comprised of inner circular and outer longitudinal muscle fibers. In the fundic region, numerous primary rugae were observed with abundant gastric glands. The pyloric region showed irregular mucosa without gastric glands. Its submucosa consisted of thicker areolar connective tissue. The intestine appeared as a small tube with folded duodenal mucosa containing deep crypts. Its epithelial mucosa consisted of columnar and mucus cells containing strong acid MPS and sulphomucins. The submucosa was thinner compared to other parts and contained fibrous connective tissue with lymphatic vessels and blood vessels. The muscular layer was dense, especially in ilial regions with long folds and abundant mucus glands. It was concluded that the tubular parts of digestive tube skipjack tuna were adapted to diet and food behaviors, as evidenced from the related functional mechanisms of fish digestive physiology.

INTRODUCTION

From an economic perspective, the Egyptian fisheries heavily rely on the Red Sea coasts, which are home to numerous economically relevant species and a large overall catch **(Mohammad, 1999)**. The Gulf of Aqaba is a short body of water, with a width of only 14 to 26km, yet it has steep walls that drop to nearly 2000m in the center. The water depth is roughly 250 meters, even at the Strait of Tiran, which is its limited (six kilometers) entrance. Tidal water inflows from the northern Red Sea, and the predominate northeast winds create surface water movement **(Salem, 1999; El-Naggar *et al*., 2022; El-Sadek *et al*., 2022)**.

The skipjack tuna (*Katsuwonus pelamis*) is a medium-sized predatory fish. The main fishing grounds for tuna purse-seine fisheries are tropical and subtropical oceans, where the fish species are extremely migratory and exhibit a seasonal prevalence. The majority of the catch is made up of skipjack **(Chang *et al*., 2022)**. Tuna fish are by nature predatory carnivores, known for their diet which includes shrimp species such as *Leptochela* sp. and *Thalassocaris* sp. In its stomach, it is likely that it does not miss any opportunity to obtain food as long as it is easily accessible **(Sivadas & Wesley, 2007)**. The most common food source for skipjack tuna is small fish, followed by mollusks and crustaceans **(Billy & Batts, 1972)**.

K. pelamis (L. 1758), is a member of the Scombridae family, and it was first observed by fishermen in the Red Sea, Egypt, in October 2021, at the beginning of a cooling trend. *K. pelamis* feeds in a modest amount. The fish are mostly scavengers, eating a variety of animals in varying proportions. The most common and preferred food item ingested by the fish was the small fish, namely *Atherinomorus lacunosus*, which was mostly devoured by *K. pelamis*, representing 79% of its stomach content **(Afifi *et al*., 2022)**.

It has been documented that piscivorous fish inhabiting coral reef ecosystems feed primarily on other fish species. This predatory behavior serves to regulate population sizes, preventing interspecies competition. These predators employ three distinct hunting techniques (pursuit, ambush, and stalking), with each necessitating specific physical adaptations and behaviors **(Lieske & Myers, 1999)**. Stalking predators rely on stealth to approach their prey undetected, exemplified by species like the skipjack tuna (*Katsuwonus pelamis*). Conversely, for ambush predators, an association has been established between the anatomical configuration of fish digestive systems and their functional mechanisms and feeding strategies **(Dasgupta, 2000)**.

The adjustments of fish digestive organs to suit their typical diet are prominently manifested in the shape, dimension, composition, density, and constraints of microscopic constituents, such as mucous cells, teeth, taste buds, muscular layers, and digestive glands found in the esophagus, stomach, pyloric caeca, and intestine. These attributes exhibit considerable and varied alterations, undergoing significant modifications corresponding to the dietary preferences of the fish **(Dasgupta, 2000; Khalaf-Allah, 2009; 2013; Alabssawy *et al*., 2019)**. The alimentary canal in fish can be categorized into the non-tubular section comprising the mouth, buccal cavity, pharyngeal cavity, and the tubular section consisting of the esophagus, stomach, and intestine **(Shalaby, 2017)**.

There is a paucity of research concerning the adaptations of the alimentary canal of piscivorous fish in the Egyptian Red Sea about their dietary preferences and feeding behaviors on needlefish, *Tylosurus choram* **(El-Deeb *et al*., 2016; Abd Elwahab *et al*., 2017)**; on corcodylefish, *Popilloculiceps longiceps* **(Alabssawy *et al*., 2019; Shalaby, 2020)** and on lizardfish, *Synodus variegatus* **(Khalaf-Allah *et al*., 2023)**.

Data regarding the morphological and histological adjustments of the digestive tract in response to the dietary preferences and feeding behaviors of the piscivorous skipjack tuna, *Katsuwonus pelamis* (L. 1758), within the Egyptian Red Sea Region, are lacking.

Therefore, the current investigation aimed to furnish a comprehensive portrayal of the morphological, histological, and histochemical adjustments observed in the tubular segment of the digestive tract of skipjack tuna (*Katsuwonus pelamis*) dwelling in Abu Galum, Aqaba Gulf, the Red Sea, Egypt, in accordance with its dietary preferences and feeding behaviors. The ultimate aim was to enhance comprehension of the pertinent functional mechanisms governing fish feeding techniques and digestive physiology.

MATERIALS AND METHODS

1. Samples collection

Individuals (ranging from 62.5 to 86cm in total length) of skipjack tuna, *Katsuwonus pelamis* Linnaeus, 1758 (Fig. 1), were gathered from the coastal waters of Abu Galum, Aqaba Gulf, the Red Sea, Egypt (N 28.264901781021806, 34.5439861895659 E) during May 2022. Longline fishing served as the primary method for fish acquisition. Whenever feasible, specimens were inspected, either in a fresh state or preserved in a 10% formalin solution, and subsequently conveyed to the Marine Biology Laboratory, Department of Zoology, Faculty of Science, Al-Azhar University, Nasr City, Cairo, Egypt, for further analysis.

Within the laboratory setting, fish were taxonomically identified by **FAO (1983)**. The total length was assessed with precision to the nearest millimeter and duly documented, followed whith the subsequent investigations.

Fig. 1. Photograph of skipjack tuna, *Katsuwonus pelamis*, collected from the Egyptian coast of Abu Galum, Aqaba Gulf, the Red Sea **(Afifi *et al*., 2022)**

2. Morphological and histological studies

To investigate the morphology, the tubular segment of the digestive tract (including the esophagus, stomach, and intestine) of *K. pelamis* was meticulously extracted from the body cavity and conserved in 70% ethyl alcohol before being documented through photography and descriptive analysis.

In preparation for histological examination, small segments of the esophagus, stomach, and intestinedissected from *K. pelamis* specimens were excised and promptly immersed in alcoholic Bouin's solution for a minimum of 48 hours. Subsequently, they underwent dehydration in progressively increasing concentrations of ethyl alcohol, followed by clearing in xylene and embedding in paraplast wax. For transverse sections, with approximately 4- 6µm in thickness, they were then sliced and stained with Harris's hematoxylin and eosin to elucidate general structural features **(Humason, 1979)**. Masson’s trichrome **(Masson, 1928)** was used for the detection of connective tissue. Alcian blue **(Putt, 1971)** was used for the detection of acid mucopolysaccharides, and Toluidine blue **(Sheehan & Hrapchak, 1980)** was used for the detection of sulphomucin. Finally, the prepared slides were subjected to microscopic scrutiny, followed by photography and detailed description.

RESULTS

1. Morphology of tubular part in the digestive tube

The tubular portion of the alimentary canal can be categorized as follows: the oesophagus, the stomach, and the intestine. The esophagus in the *K. pelamis* is characterized as a compact, muscular tube capable of expansion. Originating from the pharynx, it extends posteriorly, located a few millimeters away supported by pharyngeal teeth, and directly traverses the transverse septum, positioned ventrally to the swim-bladder, and ultimately connecting to the anterior region of the stomach. There is no distinct boundary between these two organs, except for variations in the extent of mucosal folding, as shown in Fig. (2). There are not many big mucosal folds in the esophagus (Fig. 3).

The gastric wall of *K. pelamis* exhibits a remarkable distensibility, contributing to its pouch-like (bag shape) structure and facilitating the ingestion of notably large prey items. Macroscopically, the stomach can be delineated into three distinct regions: the proximal cardiac, the mesial fundic (middle fundic), and the distal pyloric sections. Collectively, these segments compose the stomach's characteristic spindle-like morphology. The cardiac and pyloric portions seamlessly transition from the oesophagus, forming a broader curvature that converges toward the lesser curvature, and ultimately shaping the fundic region. The fundic stomach adopts a sac-like structure with a relatively expansive large lumen (Fig. 2). The distribution of large mucosal folds is sparse in the stomach, as depicted in Fig. (3).

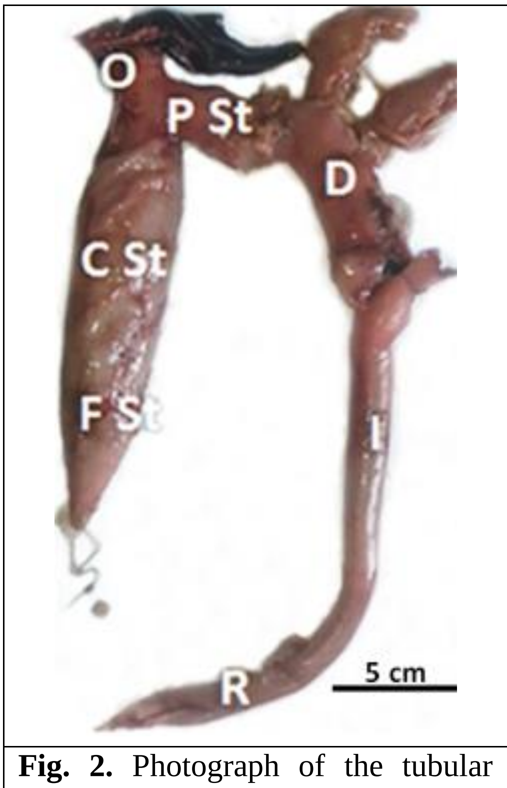

Fig. 2. Photograph of the tubular part of the digestive tube of skipjack tuna, *Katsuwonus pelamis* showing: (**O**) oesophagus, (**C St**) cardiac stomach, (**F St**) fundic stomach, (**P St**) pyloric stomach, (**D**) duodenum, (**I**) ileum, and (**R**) rectum

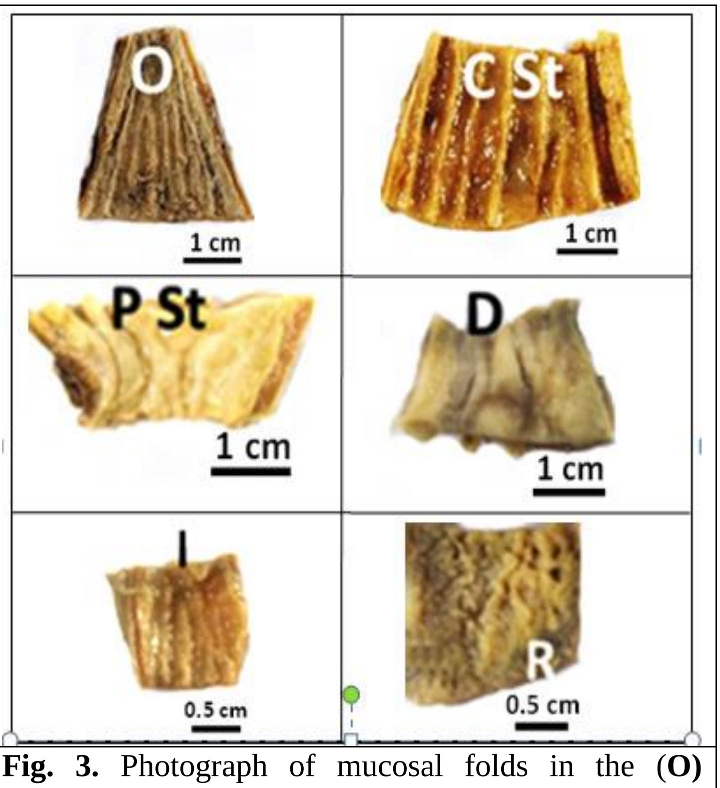

Fig. 3. Photograph of mucosal folds in the **(O)** oesophagus, (**C St**) cardiac stomach, **(F St)** fundic stomach, **(P St)** pyloric stomach, (**D**) duodenum, (**I**) ileum, and (**R**) rectum

The true intestine of *K. pelamis* is characterized as a compact, robust tube with a linear morphology with thick walls. Externally, the intestine is delineated into distinct segments, including the duodenum, ileum, and rectum, discernible by variations in diameter. The duodenum manifests as a strong portion, transitioning posteriorly into a slender descending portion (ileum) devoid of further convolutions, and culminating in a terminal segment (rectum). The rectum terminates enters into the anus on the mid-ventral line of the ventral surface, opening into the anus in its typical anatomical position (Fig. 2). In the duodenum, there are sparse large mucosal folds, while the ileum exhibits numerous mucosal folds arranged in virtually zigzag patterns, and the rectum displays abundant wavy mucosal folds (Fig. 3).

2. Histology and histochemistry of tubular digestive part

2.1. The oesophagus

The oesophagus of *K. pelamis* is a brief, contractile tube with a short muscular property. The structure of the oesophagus encompasses the typical four layers: mucosa, submucosa, muscularis, and serosa. The mucosal folds of the oesophagus exhibit irregular shapes, forming prominent primary folds that branch into secondary and tertiary folds. Multiple rows of mucus-secreting cells make up the epithelial mucosa, which are huge in size and abundant. The morphology of mucus cells might be primarily concentrated on the sides, spherical, and bases of the mucosal folds, presenting varied shapes such as saccular, pyriform, or round, while interspersed with relatively fewer squamous epithelial cells (PLATE IA, B). The mucus cells exhibit a profound blue hue upon reaction with Alcian blue, indicative of the abundant presence of potent acid mucopolysaccharides (MPS) (PLATE IC). The application of Toluidine blue stain resulted in a consistent and uniform staining reaction, suggesting the presence of sulphomucin with relatively low acidity (PLATE ID).

The submucosal layer comprises fibrous connective tissue, with larger mesh sizes adjacent to the muscular layer and smaller ones nearer to the mucosal layer. Meanwhile, the central region of mucosal folds is composed of fibrous connective tissue. The muscular layer is notably thick and consists solely of circular muscle fibers, which are striated and organized into small bundles interconnected by areolar connective tissue (PLATE IA, B).

2.2. The stomach

The stomach of *K. pelamis* exhibits a sac (bag-like) morphology, categorized into three distinct regions: the proximal cardiac, mesial fundic, and the distal pyloric regions. Each segment's wall comprises the typical four layers: mucosa, submucosa, muscularis, and serosa.

2.2.1. Cardiac stomach

In *K. pelamis*, the cardiac stomach's mucosa forms short and wide primary folds with prominent conspicuous circular apices. Comprising columnar epithelium and a dense layer of gastric glands, the epithelial mucosa lines the luminal aspect, while the gastric glands occupy the basal aspect of the mucosal folds. Columnar cells predominate in the mucosa, exhibiting slight variations in morphology, depending on their location within the membrane of mucous. These cells are abundant and characterized by a cylindrical form with wider apical regions compared to their bases. Their nuclei are oval-shaped and exhibit a recognizable chromatin network, as well as visible nucleoli (PLATE IE, F).

The structure of gastric glands is composed of straight tubular glands enveloped by connective tissue. Additionally, the gastric glands present a rounded shape with nuclei positioned peripherally in the base and elongated toward the lumen. It is accessible through a brief transitional area that leads into the base of the gastric pits. The lamina propria of primary folds is comparatively broader and consists of a densely cellular, lymphoreticular tissue abundant in granulocytes, prominent blood vessels, fibrocytes, and lymphocytes (PLATE I E, F).

Upon Alcian blue reactions, gastric glands exhibit a subtle blue hue, suggesting the presence of mildly acidic mucopolysaccharides (MPS) (PLATE IIA). In contrast, toluidine blue staining resulted in a consistent and homogeneous reaction, suggestive of the existence of marginally sulphomucins with low acidity (PLATE IIB).

The submucosal layer appears relatively slender and is made up of fibrous connective tissue populated with blood vessels and fibrocytes. The muscular layer presents considerable thickness and comprises two different layers: an inner circular muscle layer, and an outer longitudinal, both layers composed of non-striated muscle fibers. The inner layer, which is denser than the outer layer, is arranged into sizable bundles interconnected by fibrous connective tissue. Meanwhile, the serosa is made up of a simple squamous epithelium (PLATE IE, F).

2.2.2. Fundic stomach

In the fundic stomach of *K. pelamis*, the primary rugae are numerous, lower, and leave a relatively wide lumen. Gastric glands are more highly abundant; they fail to invade the epithelium (PLATE IIC). Gastric glands attain faint blue color with Alcian blue reactions, indicating the presence of weakly acid MPS (PLATE IID). The toluidine blue stain, however, gave a uniform staining reaction, indicating the presence of weak sulphomucins (PLATE IIE). The circular muscle fibers run in a circular direction yet appear wavy and undulating in cross-section. In some places, however, circumferences of muscle fibers are oblique, spiral, or even assume a radial direction. The muscularis interna is much thicker than the external one. Large lymph space and huge blood vessels are detected between the submucosa and the muscularis interna (PLATE IIC).

2.2.3. Pyloric stomach

While there is no distinct demarcation between the pyloric and cardiac sections within the stomach of *K. pelamis*, certain discernible distinctions are evident. The lumen widens upon entering the cardiac opening and narrows towards the pyloric orifice. Furthermore, the mucosa exhibits a haphazard form, forming expansive complex folds, with deep crypts and round tips. It consists of stratified squamous epithelium (PLATE IIF) and does not react with Alcian blue stain (PLATE IIIA), moreover it does not react with toluidine blue stain (PLATE IIIB). The absence of gastric glands is notable. The submucosal layer appears relatively robust, comprising areolar connective tissue, primarily inhabited by big oval fibrocytes. At the same time, the thickness of the circular muscle fibers is increaseds. A simple squamous epithelium makes up the serosal (PLATE IIF).

The intestine

The intestine of skipjack tuna, *Katsuwonus pelamis* is relatively short. Externally, the intestine is divided into various distinct areas on the outside, such as the duodenum, ileum, and rectum. The entire intestine exhibits similar histological features to other parts of the alimentary tract, with minor differences observed in the shape, height, and arrangement of the mucosal folds, as well as variations in the thickness of the intestinal wall. The wall of each portion is made up of the typical four layers: serosa, muscularis, submucosa, and mucosa. The duodenal mucosa of *K. pelamis* is greatly folded and closely set with deep crypts. They are branched to form a large number of secondary folds. The mucosal epithelial cells comprise two primary types: absorptive and more frequent mucus cells. The latter are typically sac-like or rounded in morphology and are notably concentrated at the lateral aspects and bases of the mucosal folds (PLATE IIIC).

Columnar and mucus cells attain deep blue color with Alcian blue reactions, indicating the presence of strong acid MPS (Plate 3D). Toluidine blue stain, however, gave a reddish violet color, suggesting the existence of strong sulphomucins (PLATE IIIE). It is common for lymphocytes to become located between epithelial cells, and these are highly likely to be clustered close to the basement membrane. Tunica propria is very narrow and involved with lymphocytes, fibrocytes, blood vessels, and lymph spaces. The submucosal layer is relatively slightly thinner, made up of fibrous connective tissue abundant with fibrocytes, lymphatic space, numerous large blood vessels, and lymphocytes. The muscular layers are composed of two thick distinct layers: one inner circular and one outer longitudinal layer composed of non-striated muscle fibers. In comparison to the outer longitudinal layer, the inner circular layer is noticeably thicker. The serosal covering is comprised of a simple squamous epithelium (PLATE IIIC).

The mucosal folds within the ilial of *K. pelamis* are characterized by their extensive length, high abundance, and predominantly parallel orientation, featuring deep crypts and rounded or tapering apices. Additionally, small folds or projections are observed at the crypt bases. The epithelial lining comprises broad and elongated columnar cells, interspersed with a significant population of goblet cells. Mucous-secreting cells are notably abundant, primarily concentrated at the bases of the mucosal folds, where they contribute to the creation of mucus glands (PLATES IIIF, IVA).

Mucus cells attain blue color with Alcian blue reactions, demonstrating the existence of strong acid MPS. The toluidine blue stain, however, gave a reddish violet color, indicating the presence of strong sulphomucins (PLATE IVB). Lymphocytes are more numerous. The submucosal layer is relatively slender, comprising fibrous connective tissue abundant in lymphocytes, fibrocytes, numerous prominent blood vessels, and lymphatic space. The muscular layer is underdeveloped. The serosal layer is composed of a simple squamous epithelium overlaying a delicate layer of connective tissue (PLATE IVA).

The rectal mucosal folds of *K. pelamis* are fewer in number with tapering or spherical tips. Mucus cells are numerous (PLATE IVC, D). They attain a deep blue color with Alcian blue reactions, suggesting the existence of strong acid MPS (PLATE IVE). Nevertheless, the toluidine blue stain produced a uniform staining reaction, indicating the presence of weak sulphomucins (PLATE IVF). Lamina propria is compact and contains relatively small lymph spaces. Lymphocytes are highly abundant. The submucosal layer is made up of fibrous connective tissue abundant in fibrocytes, numerous sizable blood vessels lymphatic space, and lymphocytes. The muscular layer is highly advanced, with the outer layer notably thinner than the inner. The serous connective tissue is enveloped by a thin layer of simple squamous epithelium and involves blood vessels (PLATE IVC, D).

DISCUSSION

The anatomy of the digestive system in teleosts exhibits variability, which is influenced by various factors. Its roles encompass secretion of hormones, digestion, absorption of nutrients, regulation of water and electrolyte balance for hydro-mineral homeostasis, and immune defense. This system controls the flow of energy and substances between the interior medium and the external environment. Additionally, its structure adapts and varies based on the dietary composition **(Giffard-Mena *et al.*, 2006)**. The mucosal folding across various segments of the digestive system is specific to facilitate the retention, conduction, and digestion of food consumed **(Moitra & Sinha, 1972)**.

In this study, the broad and sparsely distributed mucosal folds observed in the gastrointestinal tract of *K. pelamis,* especially in the esophagus, are distinct characteristics tailored to specific functions aimed at aiding the passage of food into the stomach. In the stomach, mucosal folds are extensive and designed to keep food in place while it is being digested. The ileum displays numerous mucosal folds arranged in nearly zigzag patterns that aid in the absorption of ingested nutrients. In contrast, the rectum mucosal folds exhibit wavy-shaped, serving to help lubricate waste matter toward the anus. These findings agree with those of **Shehata (1997a, b)**, **Khalaf-Allah (2013)** and **Shalaby (2017)**.

In the current study, a piscivorous fish such as *K. pelamis* is specially characterized as a short, narrow, and pliable muscular conduit. The considerable dispensability of the oesophagus serves as an additional adaptation for feeding purposes. In piscine anatomy, the oesophagus is typically abbreviated small and highly extensible, allowing for the ingestion of comparatively large prey items. In this regard, the oesophagus of these piscivorous specimens shares similarities with that of many other piscine species; *Tylosurus choram* **(Abd Elwahab *et al*., 2017)**, *Synodus variegatus* (**Alabssawy *et al*., 2019; Khalaf-Allah *et al*., 2023)**, and *Popilloculiceps longiceps* **(Shalaby, 2020)**.

According to this study, the mucosal folds lining the esophagus of piscivorous fish, *K. pelamis*, exhibit irregular forms, characterized by prominent primary folds that give rise to secondary, as well as tertiary folds. This intricate folding pattern enhances distensibility during food intake and augments the surface area of the esophagus for digestive processes. Additionally, mucus-secreting cells are notably very plentiful and huge in size in this region.

For the oesophageal mucosal folds of piscivorous fish, *K. pelamis* are irregular in shape. It is thrown into large primary folds, which branched to secondary and tertiary folds to increase distention during food consumption or increase the oesophageal area for digestive activities. Mucus cells are large in size and highly abundant. Based on this observation, the secretion of mucus within the gastrointestinal tract serves as the primary defense mechanism against chemical, mechanical, and physical factors, moreover, as microbial infections. Additionally, it provides a protective shielding to the mucosal lining against acidic secretions. These findings match with those obtained by **Hashem *et al.* (2012)**, **Mabrouk (2015)**, **Abd Elwahab *et al*. (2017)**, **Alabssawy *et al*. (2019)** and **Shalaby (2020)**.

The primary function of the oesophagus in fish, as in most other vertebrates, is to move parts of food from the pharyngeal chamber to the stomach. Moreover, mucous cells are supplied for lubrication (**Mujallid, 1989)**. The purpose of the oesophagus, with its extremely thick and single circular layer muscle covering, is to assist in food passage to the stomach. Mucus cells are very prevalent. As a result, food is able to move through the posterior mucosa with ease and without harming the epithelial lining. In this regard, the esophageal structure of these fish bears resemblance to that of other fish species **(Khalaf-Allah, 2001, 2009; Kozaric *et al.*, 2007; Abdel -Wahab *et al*., 2017; Shalaby, 2020)**.

According to the results of the current study, *K. pelamis*, a species of piscivorous fish, has a stomach that is highly extensible, giving it a bag-like structure that allows it to swallow rather large prey. Similar findings were detected by **Alabssawy *et al*. (2019)** and **Khalaf-Allah *et al*. (2023)** in piscivorous fish, *S. variegatus*. This outcome was at odds with the conclusions of **Shalaby (2017)**, who referred the stomach as an example that of pseudo-gaster, or pseudo stomach, as noted by the author in similar piscivorous fish, *Tylosurus choram*.

The stomach exhibits specialization for both secretion and mastication functions **(Kumar & Tembhre, 1996)**. The stomach of the piscivorous fish, *K. pelamis*, used in the current research had an extremely dense layer of muscularis in the pyloric section that helps regulate the way of food that is digested into the intestine. The cardiac and fundic sections of the stomach have a high concentration of gastric glands for the breakdown of food. These outcomes concurred with those obtained on *S. variegatus*, a piscivorous fish (**Alabssawy *et al*., 2019)** and corcodylefish, *Popilloculiceps longiceps* (**Shalaby, 2020)**. In the current study, the gastric glands are organized as linear tubular structures enveloped by connective tissue. There have been reports of similar stomach gland arrangements among various fish **(Domeneghini *et al*., 1998; Kozaric *et al*., 2007)**.

In the present study, the mucosal folds within the intestine of piscivorous fish *K. pelamis* exhibit various characteristics, with the duodenum being deeply crypted and strongly curved. These features are significantly denser in the rectum and taller and more numerous in the direction of the ileum. The ileum contains mucus glands, which offers a viscosity for both nourishment and feces particles. Mucous cells were relatively plentiful in the intestinal tract and are most prevalent near the origin of the mucosal folds. Similar findings were reported by **Khalaf-Allah (2009, 2012)**, **Mabrouk (2015)**, **El-Deeb *et al*. (2016**) and **Alabssawy *et al*. (2019)**.

In the current study, the ilial mucosal folds of *K. pelamis* are very long, large in numbers and roughly parallel to one another with deep crypts and spherical or tapering tips. The long, broad columnar cells that make up the epithelial mucosa are paired with many goblet cells to enhance the absorption region. The columnar cells are overlaid by a thin upper layer. This layer exhibits interruptions at sites where mucous cells are situated, underscoring the absorptive function of this organ. The presence of goblet cells in the distal intestine has been necessary crucial for facilitating feces lubrication. Numerous fish species showed exactly similar findings, as reported by **El–Bakary (2007)**, **Hassan (2013)**, **El-Deeb *et al.* (2016)** and **Alabssawy *et al*. (2019)**.

In the present study, mucous cells contain strong acid MPS and weak sulphomucin in the oesophagus of piscivorous fish; skipjack tuna (*K. pelamis*). The increase of acid MPS in the oesophagus may be to protect the mucosa against components of ingested fish. This finding concurs with those of **Zaiss *et al*. (2006)**, **Kozaric *et al*. (2007)** and **Shalaby (2017)** on a different fish species. They concluded that, the oesophagus contains strong acid MPS to lubricate swallowed food pieces and preserve the mucosa from, hypertonic media, acidity, parasites, and chemicals. Moreover, according to **Hashem *et al.* (2012)**, sulphomucin has been associated with a protective function. Due to the sulphomucins found in the oesophagus, the mucus has a strong viscosity, which allows for the capture of little bits **(Tibbetts, 1997)**. The increase of mucus in the oesophagus may help facilitate the flexibility nature and peristaltic movement required for lubrication of a large amount of herbal food to transfer it to the stomach. The creation of mucus inside the oesophagus helps in food swallowing and catching little pieces of food **(Hashem *et al.*, 2012; Shalaby, 2017)**.

In the present results, the stomach consists of the gastric glands of *K. pelamis* containing weakly acid MPS and weakly sulphomucins. The breakdown of extracellular material is dependent on the maturation of the stomach's gastric glands, which secrete digestive enzymes, primarily, HCL and pepsin. Advanced digesting activities, such as the digestion of proteins, need the transition between intracellular to extracellular luminal digestion **(Mabrouk, 2015)**. The widespread consensus is that fish stomach glands produce both acid and pepsinogen **(Smith, 1989)** and that neutral muco-materials have a buffering impact on the very acidity contents of the digestive trac **(Scocco *et al*., 1996; Kozaric *et al*., 2007)**.

In the current study, columnar and mucous cells layer in the intestine contain strong acid MPS. It may be due to complete digestion and more absorption of food. In addition, acid MPS has been claimed to be connected with pinocytosis and phagocytosis, where the negatively charged acid MPS plays an important role as a binding material on the cell membranes **(Kozaric *et al*., 2007; Khalaf-Allah, 2009; Purushothaman *et al*., 2016; Shalaby, 2017)**. In the current study, columnar and mucous cells in the duodenum and ileum contain strong sulphomucins. The presence of sulphomucins in the duodenum and ileum have been connected to the consumption of compounds that are simply digested.

There are several potential uses for the mucus that the intestine's goblet cells produce. In the current study, the mucous cells found within the ileum of *K. pelamis* are highly abundant and much concentrated at the base region of the mucosal folds to form mucus glands that contain strong acid MPS and strong sulphomucins. Acid MPS was demonstrated to correspond with higher mucus viscosity in the fish digestive system **(Tibbetts, 1997)** and lubricate elements that have not yet been digested, with the aim of facilitating their passage toward the rectum **(Kozaric *et al*., 2007)**. **Domeneghini *et al.* (1998)** mentioned that the movement of fluids, ions, and proteins, or a portion of them, may be regulated by the existence of mucosubstances, particularly those sulphated throughout the intestines.

CONCLUSION

The skipjack tuna, *Katsuwonus pelamis*, has an oesophagus, stomach, and intestine that are structurally appropriate for its eating pattern. Therefore, knowledge of these behaviors is essential to verifying the operational procedures related to fish digestion physiology.

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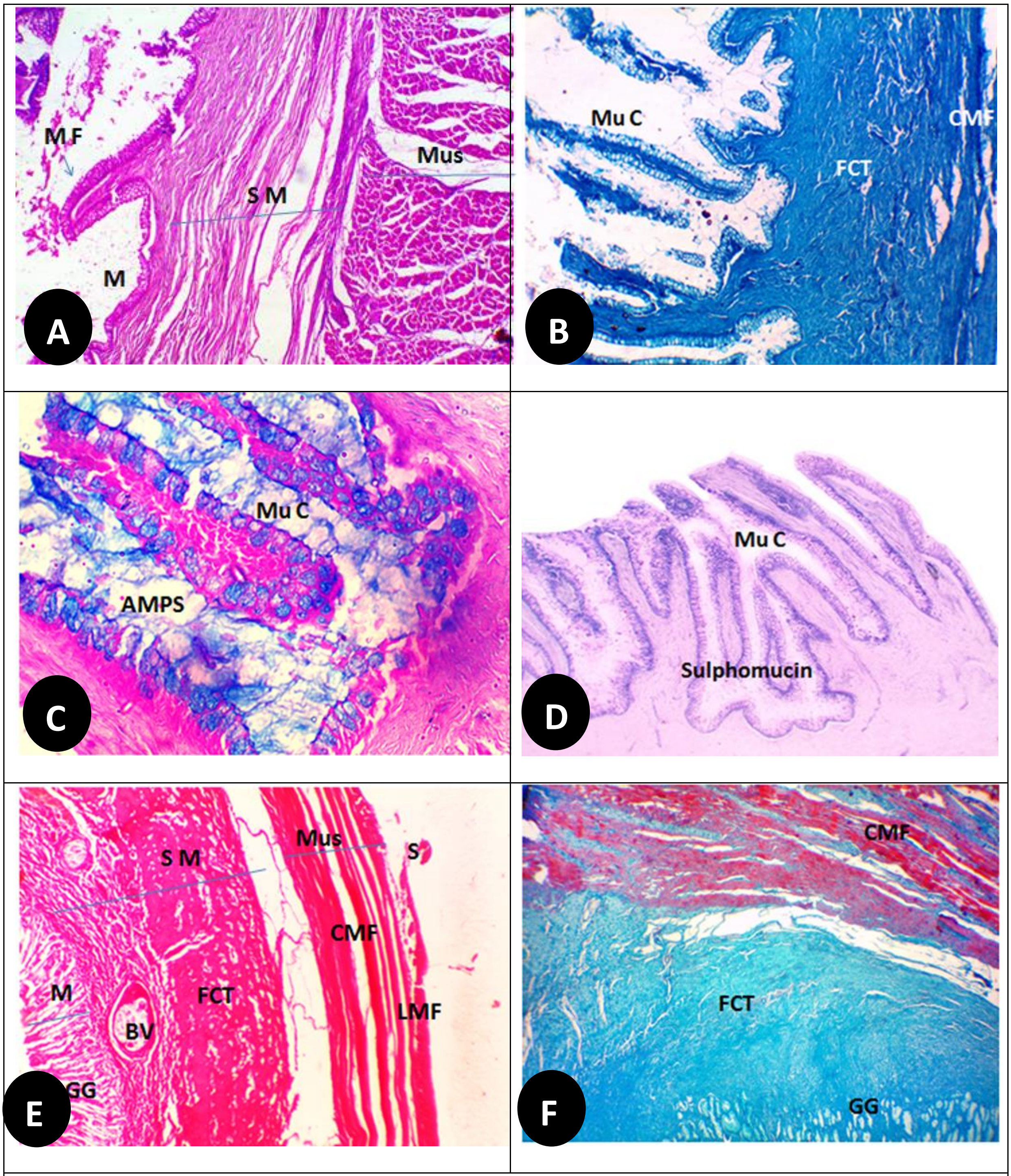

PLATE I

Photomicrographs of Sections in the tubular part of the digestive tube in skipjack tuna, *Katsuwonus pelamis*: **(A, B, C & D)** L. S. of oesophagus and **(E& F)** T. S. of cardiac stomach; showing acid mucopolysaccharides (AMPS), blood vessel (BV), circular muscle fibers (CMF), fibrous connective tissue (FCT), gastric glands (GG), longitudinal muscle fibers (LMF), mucosa (M), muscularis (Mus), mucous cells (Mu C), mucosal folds (MF), serosa (S) and submucosa (SM) (**A:** Hx & E x 40, **B:** Masson x 40**, C:** Al-PAS x 400, **D:** Toluidine blue x 40, **E**: Hx & E x 40 & **F:** Masson x 40).

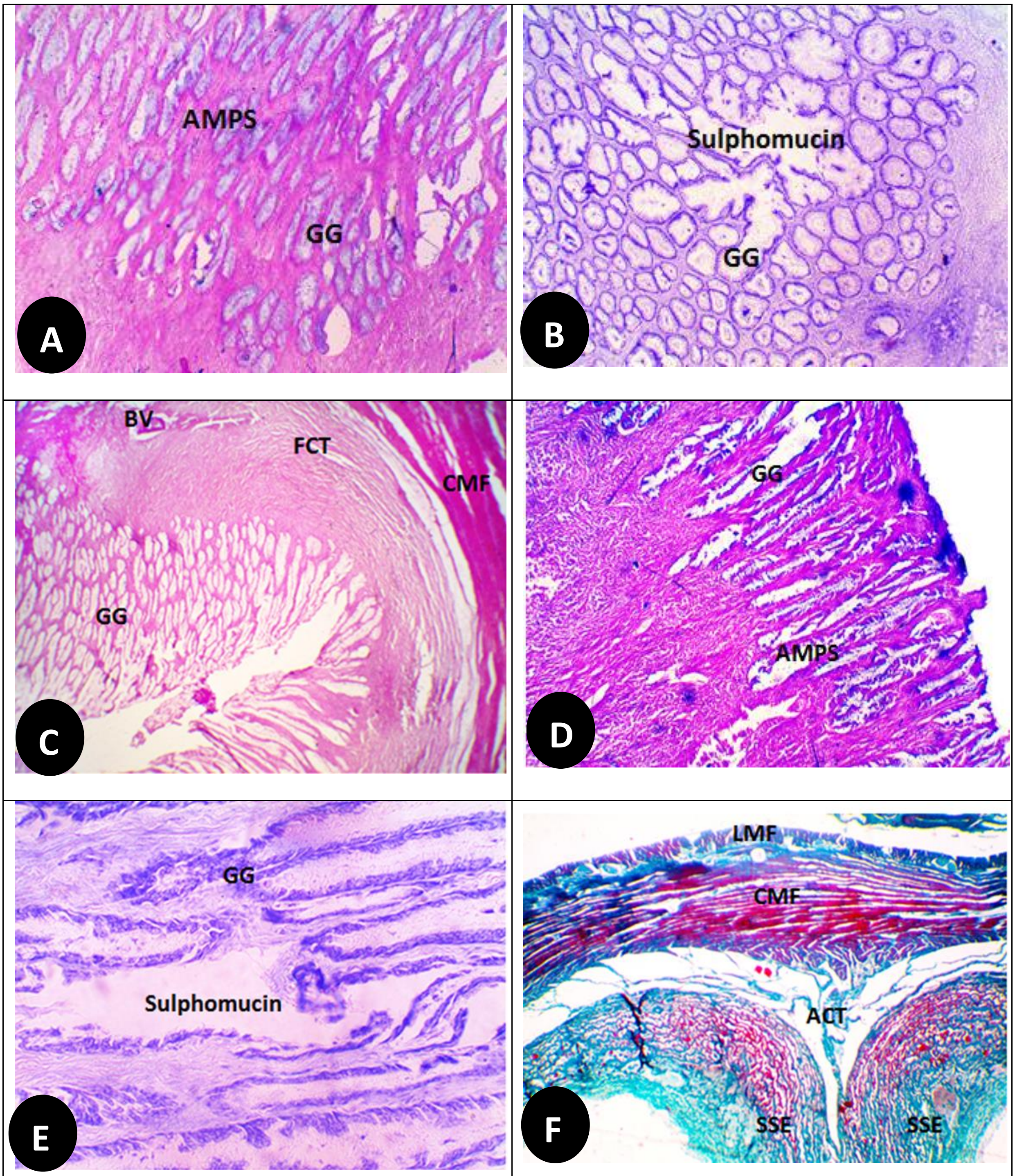

PLATE II

Photomicrographs of T. S. in the tubular part of the digestive tube in skipjack tuna, *Katsuwonus pelamis*: **(A & B)** cardiac stomach, **(C, D & E)** fundic stomach and **(F)** pyloric stomach; showing areolar connective tissue (ACT), acid mucopolysaccharides (AMPS), blood vessel (BV), circular muscle fibers (CMF), fibrous connective tissue (FCT), gastric glands (GG), longitudinal muscle fibers (LMF) and simple squamous epithelium (SSE) (**A:** Al-PAS x 100, **B:** Toluidine blue x 100, **C:** Hx & E x 40, **D:** Al-PAS x 100, **E:** Toluidine blue x 100 & **F:** Masson x 40).

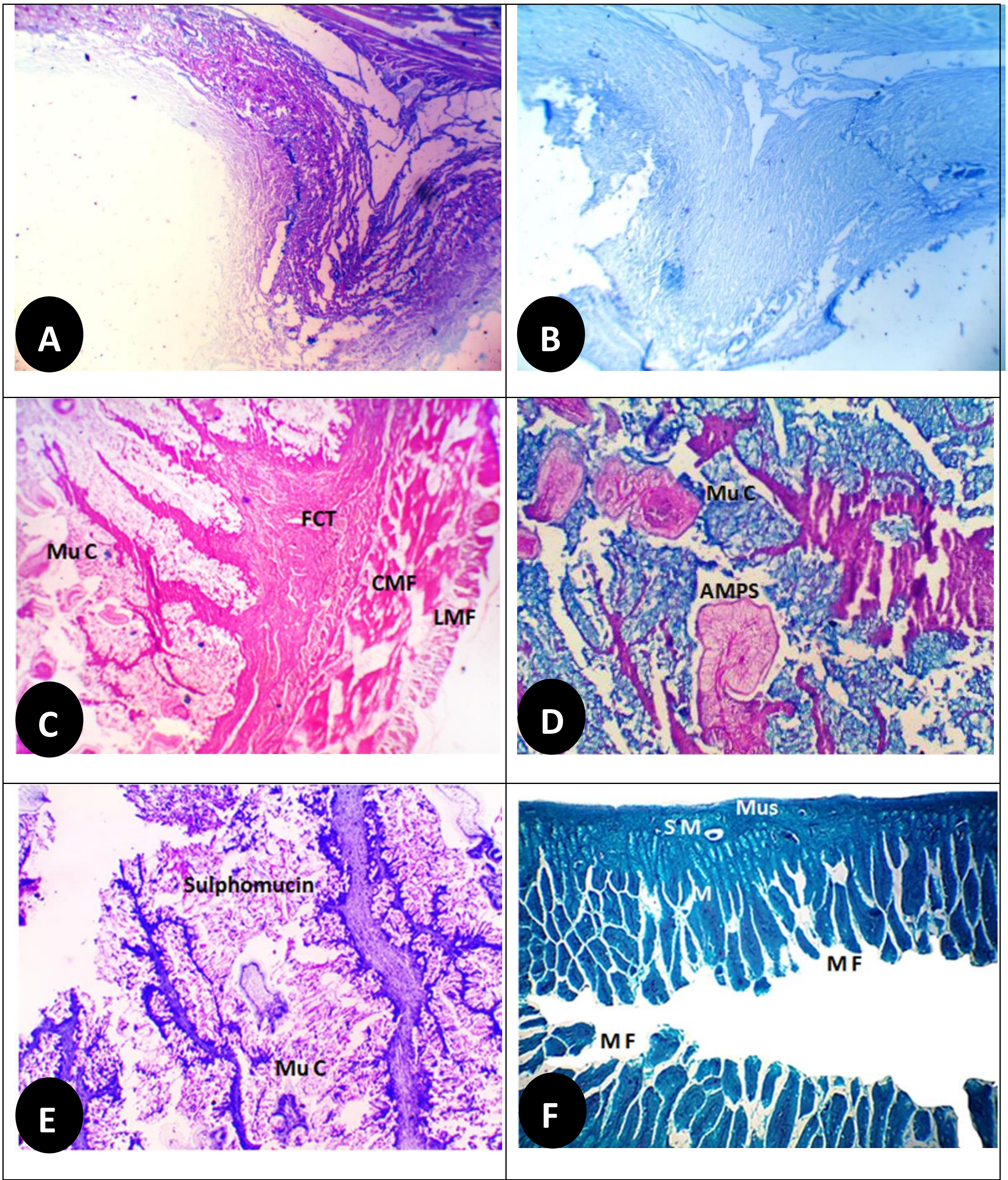

PLATE III

Photomicrographs of T. S. in the tubular part of the digestive tube in skipjack tuna, *Katsuwonus pelamis*: **(A & B)** pyloric stomach, **(C, D & E)** duodenum and **(F)** ileum; showing acid mucopolysaccharides (AMPS), circular muscle fibers (CMF), fibrous connective tissue (FCT), longitudinal muscle fibers (LMF), muscularis (Mus), mucous cells (Mu C), mucosal folds (MF) and submucosa (SM) (**A:** Al-PAS x 40, **B:** Toluidine blue x 40, **C:** Hx & E x 40, **D:** Al-PAS x 100, **E:** Toluidine blue x 100 & **F:** Masson x 40).

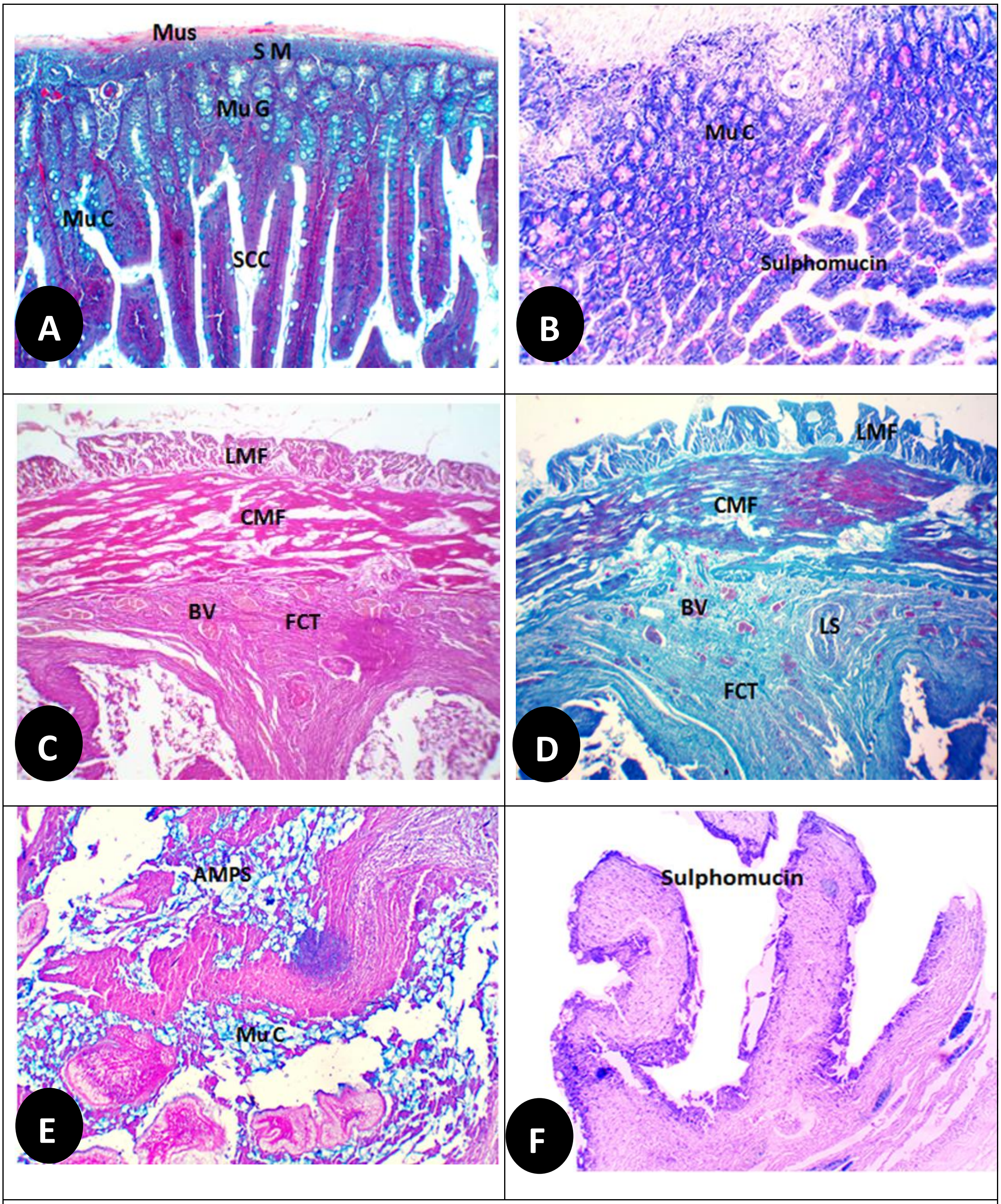

PLATE IV:

Photomicrographs of T. S. in the tubular part of the digestive tube in skipjack tuna, *Katsuwonus pelamis*: **(A & B)** ileum, **(C, D, E & F)** rectum; showing acid mucopolysaccharides (AMPS), blood vessel (BV), circular muscle fibers (CMF), fibrous connective tissue (FCT), longitudinal muscle fibers (LMF), lymph space (LS), muscularis (Mus), mucous cells (Mu C), mucous gland (Mu G), simple columnar cells (SCC) and submucosa (SM) (**A:** Masson x 100, **B:** Toluidine blue x 400, **C:** Hx & E x 40, **D:** Masson x 40, **E:** Al-PAS x 100 & **F:** Toluidine blue x 100).