Transcriptome analysis of growth variation in early juvenile stage sandfish *Holothuria scabra*

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Abstract

The sandfish *Holothuria scabra* is a high-value tropical sea cucumber species representing a major mariculture prospect across the Indo-Pacific. Advancements in culture technology, rearing, and processing present options for augmenting capture production, stock restoration, and sustainable livelihood activities from hatchery-produced sandfish. Further improvements in mariculture production may be gained from the application of genomic technologies to improve performance traits such as growth. In this study, we performed *de novo* transcriptome assembly and characterization of fast- and slow-growing juvenile *H. scabra* from three Philippine populations. Analyses revealed 66 unigenes that were consistently differentially regulated in fast-growing sandfish and found to be associated with immune response and metabolism. Further, we identified microsatellite and single nucleotide polymorphism markers potentially associated with fast growth. These findings provide insight on potential genomic determinants underlying growth regulation in early juvenile sandfish which will be useful for further functional studies.

Keywords: RNA-seq; differential expression analysis; sea cucumber; growth variation

37 **Highlights**

38

39 1. The study explores the genomic basis of growth variation in juvenile sandfish by examining
40 gene expression profiles of fast- and slow-growing early juvenile stages from three hatchery
41 populations using RNA-seq.

42

43 2. Sixty-six differentially regulated unigenes potentially related to growth variation are associated
44 with several biological and molecular processes, including carbohydrate binding, extracellular
45 matrix organization, fatty-acid metabolism, and metabolite and solute transport.

46

47 3. A large number of potential microsatellite and growth category-associated SNP markers have
48 been identified.

1. Introduction

The sandfish *Holothuria scabra* is the highest-valued tropical sea cucumber species. Processed into dried form (*bêche-de-mer* or *trepang*), it is regarded as a luxury food item in Asian markets [1]. However, the increasing global demand for sea cucumbers has led to unregulated harvesting, intensive commercial extraction, and overall decline of wild stocks and production over the past decade across many fishery areas [2], the Philippines included [3–5]. Advancements in hatchery technology [6,7] and rearing in mariculture systems [8] represent options for stock restoration and sustainable livelihood activities based on hatchery-produced *H. scabra* [9,10].

Sandfish culture practice in the Philippines involves spawning induction and production of larvae in land-based hatcheries, relocation of post-metamorphic juveniles to ocean nursery systems, followed by rearing to marketable size in pond-based or sea-pen grow-out setups [10,11]. Sandfish are transferred to nursery and grow-out systems upon reaching suitable size and weight. Juveniles can be moved to nursery systems upon reaching lengths > 4 mm (on average 35-40 days post-settlement) and can be transferred to grow-out systems upon reaching > 3 g (typically 30-60 days nursery rearing) [11]. Consequently, faster-growing juveniles reaching minimum size limits can be can be transferred to ocean nursery and grow-out systems in a shorter period compared to their slower-growing cohorts. Transfer of juveniles to ocean-based nursery systems represents significant reduction in production costs associated with hatchery operations and maintenance and may increase production efficiency with the hatchery potentially accommodating more larval production cycles. Reducing the cost of juvenile production is important for economic viability and to advance sandfish culture to commercial scales.

71 Growth is a key performance trait of economic importance in aquaculture [12]. Sea
72 cucumbers exhibit high levels of individual growth variation with coefficient of variation (CV)
73 exceeding 50% [13,14]. Individual growth variation has been attributed to environmental effects
74 during rearing, with higher stocking densities resulting in increased CVs for two sea cucumber
75 species, *Apostichopus japonicus* [13,14] and *H. scabra* [15]. In *A. japonicus,* while crowding stress has
76 a negative effect on food intake, energy allocation and growth of smaller individuals [13,14], genetic
77 factors are still considered to exert significant influence on growth heterogeneity [13]. Improving
78 culture production systems require a better understanding of the factors affecting the growth of
79 individuals, including genetic variability. [16,17]. Thus, uncovering genomic determinants for growth
80 performance are of scientific and commercial interest. The advent of next-generation sequencing
81 (NGS) technologies has enabled genome- and transcriptome-wide studies, representing
82 opportunities towards the development of genomic technologies to enhance aquaculture
83 production efficiency and sustainability even for non-model organisms[18]. RNA sequencing
84 technology (RNA-seq) is one of the more powerful high-throughput sequencing approaches to
85 identify and profile candidate genes related to differences in production and performance traits
86 [19,20], discover genetic markers for population genetics [21,22], and phenotypic variation investigations
87 [23,24].

88 Genetics-based studies on individual growth variation in sea cucumbers are currently
89 limited to *A. japonicus*, based on RNA-seq for comparative analysis of gene expression
90 profiles[25,26]. It remains uncertain, however, whether observations from *A. japonicus* are generally
91 applicable to other sea cucumber species such *H. scabra* . In this study, we performed genome-
92 wide transcriptome analysis of *H. scabra* using RNA-seq to infer genetic mechanisms potentially
93 underlying growth variation in the species. We performed *de novo* assembly and characterized the

transcriptome of early juvenile stage *H. scabra* from three different Philippine populations. We also examined differential expression profiles of slow- and fast-growing juveniles and identified potential single nucleotide polymorphism (SNP) markers associated with individual growth variation. The results contribute towards improving our understanding of transcriptome-level regulatory mechanisms underlying individual growth variation in juvenile *H. scabra*. This study contributes genomic resources to enable the development of genome-based technologies for aquaculture and fisheries management through marker-assisted selection, population genetics and adaptation studies in sandfish.

2. Materials and methods

2.1. Sample Collection

Holothuria scabra were sampled at two early life history stages. Juveniles were produced at three hatchery facilities: University of the Philippines - Bolinao Marine Laboratory (BOL), Pangasinan; Palawan Aquaculture Corporation, Coron, Palawan (PAC), and; Alson's Aquaculture Corporation, Alabel, Saranggani (AAC). The locations of these facilities are shown in Figure 1A. At each hatchery, mass spawning of 40-50 adult sandfish was induced [27]. Developing larvae were reared in larval tanks for 45 days post-fertilization (Stage 1). Each cohort was then sorted into two growth categories according to body length: (i) fast-growing group ('shooters', SHO; with total length (TL) ≥ 3.5 mm) and (ii) slow-growing group ('stunted', STU; TL < 2 mm (Figure 1B). All samples from SHO and STU were immediately preserved in RNA*later* (Ambion, Inc., TX, USA) and stored at -20°C until further processing. For Stage 2 juveniles (sand conditioning stage), another cohort was produced and reared for 75 days post-fertilization. The body wall tissues of individuals from SHO (TL ≥30 mm) and STU (TL ≤10 mm) were biopsied, preserved in

117 RNA*later*, and stored at -20 °C until use. Stage 2 samples were only collected for BOL and were
118 only included for the *de novo* assembly.

119 **2.2. Total RNA extraction, cDNA library construction, and transcriptome sequencing**

120 Total RNA was extracted from sandfish juveniles using RNeasy Mini Extraction Kit
121 (QIAgen, CA, USA) according to the manufacturer's instructions. Due to the small size of
122 juveniles, individuals were pooled to ensure recovery of adequate amounts of RNA for sequencing.
123 For Stage 1, each extraction column contained a pool of 7 whole individuals from SHO and 40
124 whole individuals from STU. For Stage 2, a ratio of 1 SHO: 4 STU was used. RNA quantity and
125 purity were assessed using BioSpec Nano (Shimadzu, Kyoto, Japan) and RNA quality was
126 validated (RNA integrity number > 8) using an Agilent 2100 Bioanalyzer (Agilent Technologies,
127 CA, USA). For Stage 1, biological replicates for each growth category at each of the 3 hatchery
128 populations were prepared for high-throughput sequencing. Stage 2 had no replicates.

129 cDNA library construction and sequencing were performed by the Beijing Genomics
130 Institute (BGI; Shenzen, China). Library preparation was performed using the Illumina TruSeq™
131 RNA sample prep kit. A total of sixteen libraries were sequenced on an Illumina HiSeq 2000
132 (100 bp, paired-end).

133

134 **2.3. Pre-processing, *de novo* assembly, and quality assessment**

135 Initial adapter quality filtering of the raw reads was performed by BGI, which included
136 removal of adapter sequences and reads with ambiguous bases higher than 5%. Further read
137 filtering and trimming was performed using BBDuk from the BBMAP suite v36.11[28]. Reads with
138 overall Q < 20 and with < 70 bp after trimming were further discarded. Error-correction was

139 applied to all reads using Rcorrector v1.0.2[29]. FastQC v0.11.5 [30] was used to assess the quality of
140 raw and processed reads.

141 *De novo* transcriptome assembly was performed using clean reads from all libraries with
142 *in silico* normalization using default Trinity v2.8.4 parameters [31,32]. To reduce redundancy, contigs
143 from the assembly were clustered using CD-HIT v4.6 with -the following parameters: -s 0.9 -aS
144 0.9. Transrate v1.0.3 [33] was used to filter sequences with low contig scores. Further clustering of
145 potentially related transcripts was carried out using Corset v1.09 [34] and salmon v1.1[35] . The longest
146 sequence for each cluster was considered as a "unigene." Finally, unigenes tagged by
147 Transcriptome Shotgun Assembly (TSA) online submission as contaminants were removed in the
148 final assembly.

149 Assembly quality and completeness were evaluated using proportion of reads that could be
150 mapped back to transcripts (RMBT), contig ExN50 statistics, Transrate, and BUSCO v3.0.2[36].
151 RMBT was determined by aligning all clean reads to the final assembly using Bowtie2 v2.2.5 [37]
152 and ExN50 was computed using a combination of scripts bundled with Trinity package.

153

154 **2.4. Functional annotation of *H. scabra de novo* transcriptome assembly**

155 Unigenes were queried against various databases and tools capable of predicting potential
156 function of a sequence. Annotation using NCBI non-redundant protein database (nr) was carried
157 out through DIAMOND blast v0.9.29. Unigene annotation was also conducted using Trinotate
158 v3.1.13 (https://trinotate.github.io), which performed sequence homology searching against the
159 SwissProt database [38] using blast [39], PFAM database [40] by HMMER v3.1 [41], and association with
160 Gene Ontology (GO) terms [42]. Trinotate was also used to predict open reading frames (ORFs) by
161 TransDecoder v5.3.0 (http://transdecoder.sourceforge.net), transmembrane region prediction by

162 tmHMM v2 [43], signal peptide cleavage site prediction by signal v4 [44], respectively. In addition,
163 ORFs were also used to search against the eukaryotic ortholog groups (KOG) using webMGA [45]
164 and eggNOG v4.5.1 database using eggNOG-mapper [46]. Kyoto Encyclopedia of Genes and
165 Genomes (KEGG)[47]metabolic pathways assignments were performed using the SBH method in
166 the online KEGG Automatic Annotation Server (KAAS)[48]).
167

168 **2.5. Differential expression analysis between SHO and STU**

169 Gene-level differential expression analysis was performed using tximport [49] and DESeq2
170 [50]. Differential gene expression analysis was only performed on Stage 1 samples due to the lack of
171 replicates for Stage 2. Confounding factors (e.g. batch effects) due to interpopulation variation
172 may not be fully accounted for if DE analysis is performed between SHO and STU across hatchery
173 datasets, which may result in DE inaccuracies. Therefore, DE analysis was performed by
174 comparing SHO against STU for each hatchery dataset. Differential expression of unigenes
175 (DEUs) were considered significant if $|\log_2 FC| \geq 2$ and an adjusted p-value [51] of < 0.01 was
176 observed.

177 **2.6. GO and KEGG enrichment analysis of differentially expressed unigenes**

178 GO enrichment analysis of the DEUs was performed using the GOseq [52] based on the
179 Wallenius' noncentral hypergeometric distribution to adjust for gene length bias in the
180 differentially expressed genes. GO terms with corrected p-value < 0.05 were considered
181 significantly enriched. KEGG Pathway enrichment analysis of DEUs was performed using the
182 online tool KOBAS 3.0 [53]. Reference database for *S. purpuratus* was used as background and
183 hypergeometric test/Fisher's exact test with FDR-correction [51] and a cutoff of < 0.05 was used to
184 test whether identified enriched pathways were significant.

185

186 **2.7. Identification of DNA variants: microsatellites and SNPs**

187 MISA [54] was used to identify the potential simple sequence repeats (SSRs) or microsatellite
188 markers in the assembled transcriptome. The parameters were adjusted for identification of at least
189 10 repeats for perfect mononucleotide motifs, six for dinucleotide, and five for tri-, tetra-, penta-,
190 and hexa-nucleotide motifs.

191 SNPs discovery was performed using the KisSplice v. 2.4.0-p1 pipeline [55]. The complete
192 pipeline also allows the evaluation of condition-specificity by testing whether there is a significant
193 association between a SNP and a specific condition (using kissDE v.1.5.0). All programs used in
194 the pipeline were run using default parameters. Only biallelic SNPs were used for downstream
195 analysis.

196

197 **2.8. Hardware and other software used**

198 DE analyses, including DESeq2 and GOseq, were performed using RStudio [56], with graphs
199 generated using ggplot2 [57], dplyr [58], tidyverse [59], and pheatmap [60]. Bioinformatics analyses were
200 performed using either of two local workstations: (i) 6 core Intel® Core(TM) i7-5820K CPU @
201 3.30GHz, 4 x 16GB DDR4; and (ii) 2 x 6 core Intel® Xeon® Processor E5-2620 v3 @ 2.4GHz; 8
202 x16GB DDR4). Both computers run on Ubuntu 16.04.

203

204 **3. Results and Discussion**

205 **3.1. Sequencing and *de novo* transcriptome assembly for *H. scabra***

206 To elucidate the genetic basis of growth variation in sea cucumbers, we performed a
207 comparative analysis of gene expression profiles of two growth categories designated as fast-

growth (SHO) and slow-growth (STU) in early juvenile stage *H. scabra*. Samples were obtained from three different hatchery populations and sequenced using RNA-Seq.

Over 347 million 100 bp pre-processed reads were obtained from sixteen libraries. Approximately 298 million high-quality paired reads were retained after further trimming, filtering, and error correction (Additional File 1 Table S1) and were used for *de novo* assembly. The initial Trinity assembly generated 369,886 transcripts with a N50 of 1,835 bp, Transrate score of 0.04 (optimal = 0.1), and BUSCO metrics of 94% complete, 5.9% fragmented, and no missing ortholog from the eukaryote database. Reducing the redundancy of the initial assembly resulted in a final assembly consisting of 147,981 unigenes with a N50 of 1,572 bp, average sequence length of 961.1 bp, and a GC content of 38.2 (Table 1).

Assembly quality was further evaluated using different approaches. Transrate, which estimates the overall quality of the assembly based on the original reads, revealed an assembly score of 0.339 for the *H. scabra* transcriptome, a score higher than the generally acceptable score of 0.22 [33]. Transcriptome completeness scores using BUSCO showed that the final assembly was 94.1% complete and 4.3% fragmented. Our assembly exhibited low levels of missing single-copy orthologs (1.6% missing), indicating good coverage and quality of the assembly.

To further evaluate the quality of the *de novo* assembly, RMBT and Nx metrics were also calculated. The juvenile sandfish assembly showed a RMBT range of 89.8% - 97.5% and a contig N50 of 1,572 bp. Additionally, ExN50 was calculated as it has been suggested to be more informative than the contig N50, and therefore a more reliable measure of transcriptome assembly quality [61]. Our assembly showed peak saturation point at 78% of the normalized expression data (E78N50), corresponding to a contig length of 2,559 bp (Additional File 2 Figure S1). Higher quality transcriptome assemblies, however, are expected to produce N50 peak of ~90% (E90N50)

231 of the total expression data [61]. Lower than E90N50 may indicate that more reads are needed for
232 the assembly. Nonetheless, considering the other quality evaluation metrics used (Transrate,
233 BUSCO, and RMBT), we still assessed the reference assembly to be of good quality and suitable
234 for transcriptome analyses, including marker discovery and differential gene expression analysis.
235

236 **3.2. *H. scabra* transcriptome assembly annotation**

237 Unigenes were translated into proteins using Transdecoder, which predicted 26,124
238 sequences potentially containing coding regions of at least 100 amino acids in length. In total,
239 25,761 unigenes (16.7% of the total sequences) were assigned with significant annotations from
240 at least one of the seven query databases (Table 2). The highest number of unigenes with
241 significant hits was reported from nr (16.2%), followed by SwissProt (11.3%), GO (11.5%), PFAM
242 (9.8%), and eggNOG (9.1%). Focusing on unigenes with predicted coding regions, a total of 81.1%
243 (21,195 unigenes) had a significant annotation in one of the query databases. The species
244 distribution from blasting the assembly against nr is shown in Figure 2A. Among the top 15 most
245 represented species, the majority of hits belonged to another holothuroid (*A. japonicus*, 20,344
246 unigenes), followed by the purple sea urchin *S. purpuratus* (Class Echinoidea; 2,236), and crown-
247 of-thorns *Acanthaster planci* (Class Asteroidea; 1,930).

248 Unannotated unigenes could be attributed to lack of genomic data in public databases for
249 *H. scabra*, misassembled transcripts or chimeras, non-coding (nc) RNAs, and mRNAs that are
250 potentially novel and holothurian-specific[62]. Notably, at least 1,200 sequences in the assembly
251 contain complete protein sequences, ≥ 100 residues in length, and ≥ 10 supporting reads but
252 showed no homology with any genes in the databases used for annotation (data not shown).

253 To identify and characterize the corresponding functions of the assembled *H. scabra*
254 transcriptome, unigenes were queried against the GO and KOG databases. A total of 5,625
255 unigenes with predicted ORFs were assigned to one or more KOG annotations (Figure 2B). Among
256 the KOG categories, the "general function prediction only" comprised the largest proportion
257 (17.2% of unigenes with KOG hits), followed by "signal transduction mechanisms" (12.1%). For
258 GO-based annotation (level 2), a total of 17,764 unigenes was mapped to at least one GO term
259 (Figure 2C). Of these, 15,132 unigenes were assigned to Biological Processes (BP), 16,094 to
260 Cellular Components (CC) and 15,538 to Molecular Function (MF). Within the BP category,
261 "cellular process" (13,550 unigenes) and "metabolic process" (10,207) sub-categories were the
262 most represented, while "cell" (14,221) and "cell part" (14,198) were the predominant sub-
263 categories under CC, and "binding" (12,030) and "catalytic activity" (7,678) for MF. Moreover,
264 genes tagged under the term "regulation of growth" (GO:0040008) were also identified, which
265 included sodium- and chloride-dependent GABA transporter 1, nipped-B-like protein A, and
266 signal transducers and activators of transcription 5B (for the complete list, see Additional File 1
267 Table S2). For characterization of the active biological pathways, unigenes were also queried
268 against KEGG Orthology database. A total of 13,173 unigenes were annotated to 391 KEGG
269 pathways and were classified into 34 pathway categories (Figure 2D). The highest number of hits
270 was identified under the general term "global and overview maps" with 1,477 unigenes with
271 successful hits, followed by "signal transduction" (1,453) and "endocrine system" (743). Using *S.*
272 *purpuratus* pathway maps as reference for KEGG analysis, 127 metabolic pathways were
273 recovered (Additional File 1 Table S3). The most represented pathway was "metabolic pathways"
274 (1,827 unigenes), followed by "neuroactive ligand-receptor interaction" (332), and "endocytosis"
275 (209).

276

277 **3.2. Gene expression profile comparison of SHO and STU sandfish juveniles**

278 Our results revealed different DEU profiles for the three datasets representing each of the
279 hatcheries. DESeq2 recovered the greatest number of DEUs in AAC (1,324), followed by BOL
280 (831), and PAC (408) (Figure 3A). Differences in DEU profiles across hatcheries may be due to
281 varying physico-chemical conditions during rearing (e.g. temperature, water quality) in different
282 geographic regions. Inherent genetic variation among samples from different biogeographic
283 regions also likely account for DEU profile differences. A population genetic study on *H. scabra*
284 reports genetic divergence among populations of sandfish representing the major marine
285 biogeographic regions in the Philippines [63].

286 All three populations shared 66 DEUs that exhibited consistent expression patterns, where
287 45 and 19 were upregulated and downregulated, respectively (Additional File 2 Figure S2). Of the
288 66 DEUs, 30 unigenes were assigned with significant (eval: $< 1E^{-10}$) nr annotation (Table 3), while
289 the remaining 36 had no significant hits and potentially encode long non-coding RNA (Additional
290 File 1 Table S4).

291 To provide a general overview of the main functions of the identified DEUs, we also
292 performed GO and KEGG analyses on each hatchery dataset. GO terms associated with the DEUs
293 in all datasets were dominated by "cell," "cell part," and "membrane," for CC, and "catalytic
294 activity" and "binding" for MF (Additional File Table S5). GO terms "metabolic process,"
295 "cellular process," and "biological regulation" were among the most represented GO terms under
296 BP. DEUs in each dataset were observed to be involved in several KEGG pathways but were
297 generally assigned to the following sub-pathways: "global and overview maps," "lipid
298 metabolism," "digestive system," and "transport and catabolism" (Additional File Table S6).

299

300 **3.3. Enrichment analyses of differentially expressed unigenes**

301 Considering that DEU profiles differ considerably among hatchery datasets, we focus on
302 unigenes, enriched GO terms and KEGG pathways that were concordant across hatcheries (AAC,
303 BOL, and PAC); these provide stronger evidence for differential growth and a more robust
304 biological signal of genes and related functions associated with growth variation in sandfish
305 juveniles. Thus we focus our discussion on 30 DEUs that showed consistent expression patterns
306 across all three populations, identified as "key DEUs" (Table 3). We also considered as significant
307 those DEUs that are common between two populations and functionally related to the key DEUs
308 (Additional File 1 Table S7).

309

310 **3.3.1. GO enrichment analysis**

311 GO enrichment analysis using GOSeq showed highest number of significant (FDR < 0.05)
312 enriched GO terms in AAC (51 terms), followed by PAC (26), and BOL (2) (Additional File 1
313 Table S8). Enriched GO terms observed in all populations were only related to "carbohydrate
314 binding" (GO:0030246) and "extracellular region" (GO:0005576).

315

316 **3.3.1.1. DEUs associated with carbohydrate binding**

317 Four key DEUs were enriched in "carbohydrate binding": lactose-binding lectin l-2-like),
318 C-type lectin 4-like, mannan-binding C-type lectin, and ladderlectin. Notably, these were
319 annotated as genes with C-type lectin-like domains (CTLDs) and, except for the putative C-type
320 lectin 4-like, were all upregulated in SHO. Interestingly, other CTLD-type DEUs were also
321 upregulated in two populations, including putative L-rhamnose binding lectin and ficolin. CTLD

322 proteins are calcium-dependent pattern-recognition receptors (PRRs) that can recognize and bind
323 to carbohydrate moieties (microbe-associated molecular patterns, MAMPs) on microorganisms
324 and activate several immune responses to eliminate pathogens, including the complement pathway,
325 agglutination and immobilization, opsonization, phagocytosis, and lytic cytotoxicity [64,65]. SHO
326 samples showed upregulation of CTLD genes, which suggests enhanced immune response
327 compared with STU. An intriguing possibility is that immune response to possible pathogen
328 invasion in SHO primarily involves lectin-mediated antimicrobial activities, with CTLD proteins
329 potentially acting as signal receptors, opsonins, agglutinins, or direct antimicrobial effectors.
330 However, not all CTLD genes are deregulated during infection [65,66]. Therefore, whether differential
331 expression of these immune-related genes is an exclusive consequence of pathogen-dependent
332 immune response remains unclear. Interestingly, we also detected amassin, an upregulated key
333 DEU involved in defense and immunity of echinoderms [67], together with several upregulated
334 DEUs common in two populations that are immune-related, including macrophage mannose
335 receptor 1-like, sushi, von Willebrand factor type A, and IgGFc-binding protein. Induced activity
336 of these genes suggests immune response in SHO is highly activated.
337
338 **3.3.1.2. DEUs associated with extracellular region**
339 The GO term "extracellular region" was also enriched across all populations. Key DEUs
340 identified under this term were ladderlectin, natterin-3, deleted in malignant brain tumors 1 protein
341 (*DMBT1*), short-chain collagen C4 (*CAS4*), proprotein convertase subtilisin/kexin type 9 (*PCSK9*),
342 and thrombospondin-1 (*TSP1*).
343 The connective tissue of echinoderms comprises extracellular matrix (ECM) proteins,
344 dominated by collagens, proteoglycans, and fibrillin microfibrils [68]. Proteolytic activities on ECM

345 components are activated to allow ECM transformation and remodeling during pivotal
346 developmental processes, such as morphogenesis, organ development, autotomy, and regeneration
347 [68–70]. In SHO, we identified upregulated genes involved in ECM modification, which may suggest
348 higher ECM remodeling rate, possibly as a result of faster tissue and organ growth and
349 development. Two key DEUs matched to *CAS4*, which encodes a variant of collagen IV [71]. Little
350 is known on the role of spongin-related proteins in ECM of echinoderms, but they are assumed to
351 have potentially similar function to collagen IV, including involvement in cell-matrix adhesion,
352 intercellular cohesion, and organismal organization [72]. In addition, we identified an upregulated
353 DEU homologous with *PCSK9*, an extracellular serine protease that generally performs proteolytic
354 degradation of structural components of ECM (e.g. collagen) to facilitate remodeling of the
355 connective tissue of different organs [68,73]. Furthermore, DEUs related to ECM-related proteins
356 were identified in two populations, including fibrillin-1, fibropellin-1-like, N-
357 acetylgalactosamine-6-sulfatase, and several serine-type proteases such as *PCSK9* homologs,
358 cuticle degrading serine protease, serine proteinase, chymotrypsinogen-A, and tolloid-like protein.
359 Consequently, these differentially expressed ECM-associated genes potentially play roles in the
360 growth variation in juvenile sandfish by regulating ECM and connective tissue modification.

361 The key DEU ladderlectin, a gene encoding an extracellular CTLD protein has been
362 suggested to be vital in pathogen clearance because of its ability to opsonize bacteria and viruses
363 [74,75]. Although the function of ladderlectins in marine invertebrates remains underexplored, it is
364 possible that observed upregulation confers enhanced immunity in SHO, as reported in fish
365 species [74,76]. A *DMBT1*-like gene was also differentially expressed between STU and SHO.
366 Sandfish *DMBT1* contains the canonical domains CUB, SRCR, and zona pellucida, which have
367 been implicated in the mediation of protein-protein interactions [77]. *DMBT1* has been suggested to

368 be involved in host disease susceptibility and resistance [78,79] and in different developmental
369 processes [80,81]. A natterin-like gene sharing similar domains (i.e., functionally uncharacterized
370 DUF3421 superfamily and an aerolysin-like pore-forming domain) with naquin (*Thalassophryne*
371 *nattereri*) natterins was also found to be differentially expressed in all hatchery datasets [82]. We
372 also identified a DEU upregulated in AAC and PAC that is homologous with natterin-3 of *A.*
373 *japonicus*. It has been shown that proteins encoded by natterin-like genes can bind and degrade
374 type I and IV collagen and has the ability to destroy pathogens through pore-like complex
375 formation on the target cells, which eventually undergo lysis [83]. It is plausible that upregulation of
376 these natterin-like genes in SHO influences growth through immune-related mechanisms.

377 Of the unigenes associated with "extracellular region" that are common across all hatchery
378 datasets, only *TSP1* was upregulated in STU compared to SHO. TSP1 is a trimeric matricellular
379 glycoprotein that has been associated with a wide range of biological functions, including cell
380 adhesion, cell growth, and modulation of cell-to-cell signaling and cell-ECM interactions [84]. The
381 upregulation of *H. scabra TSP1* in STU is likely to exert an inhibitory effect on growth and
382 development by suppressing the activity of TSP1 targets that regulate growth-related biological
383 activities, such as cellular receptors (e.g. VEGF receptor [85]) and ECM molecules (e.g. MMPs [86]).
384

385 **3.3.2. KEGG enrichment analysis**

386 KEGG enrichment analysis revealed the highest number of significantly enriched pathways
387 (FDR $p < 0.05$) in AAC with 11 identified KEGG pathways, followed by the BOL and PAC
388 datasets with ten pathways each (Additional File 1 Table S9). KOBAS identified three enriched
389 KEGG pathways common to all populations, namely, "metabolic pathways," "retinol
390 metabolism," and "phagosome."

391

392 **3.3.2.1. DEUs associated with metabolic pathways**

393 Metabolic pathways (spu01100) comprises several subpathways, including carbohydrate
394 metabolism and energy metabolism. In metabolic pathways, we identified three key DEUs present
395 in all populations, namely, alpha-amylase 2B (*AMY2B*), histidine ammonia-lyase (*HAL*), and
396 alkaline phosphatase (*ALP*).

397 *AMY2B* encodes for an enzyme that catalyzes the first step in the digestion of dietary starch
398 and glycogen, and thus plays an important role in digestion and energy metabolism. In addition, a
399 DEU similar to sucrase-isomaltase, intestinal-like (*SI*), which is another carbohydrate-degrading
400 enzyme, was identified in the BOL and PAC datasets. Many digestive enzymes, including AMY2B
401 and SI, are endogenous in origin [87,88] and their activity can be modulated based on the substrate
402 availability [89,90]. Consequently, upregulation of *AMY2B* and *SI* in SHO could be a result of
403 increased dietary carbohydrate intake, probably to support the energetically costly metabolic
404 processes concomitant with growth. Growth rate, food intake, and food conversion efficiency has
405 been shown to be generally higher in larger *A. japonicus* individuals compared to their smaller
406 cohorts [91].

407 *HAL* is a gene encoding for an enzyme that catalyzes the first reaction in histidine
408 degradation to urocanic acid and ammonia [92]. In murine models, high-protein diet has been shown
409 to increase *HAL* expression and concomitantly lower the histidine serum concentrations while
410 undernutrition has been shown to reduce *HAL* activity and decreased overall growth as a
411 consequence of preventing degradation of amino acids, such as histidine, under a condition of
412 dietary protein limitation [93,94]. Thus, we speculate that lower *HAL* expression in STU compared
413 with SHO may be a consequence lower feeding rate in slow-growing individuals. We also

414 identified a DEU (Cluster-4263.3269) homologous with histamine N-methyltransferase-like
415 (*HNMT*), which exhibited lower expression in SHO compared with STU in AAC and PAC. *HNMT*
416 encodes for an enzyme that catabolizes histamine to 1-methylhistamine [95]. While speculative, it is
417 possible that higher availability of the histamine-precursor histidine, due to lower *HAL* expression
418 in STU, allows elevated histamine concentration, subsequently causing the upregulation of
419 histaminase *HNMT*. Histamine suppresses feeding in rats in high levels [96] and has also been
420 suggested to play a role in feeding behavior of sea cucumber *Leptosynapta clarki* [97]. Nonetheless,
421 the potential associations between *HAL*, *HNMT,* histamine activity, and feeding and growth
422 variation of juvenile sea cucumbers should be experimentally validated in the future.

423 The final key DEU in metabolic pathways is *ALP*, which encodes the enzyme tissue
424 nonspecific alkaline phosphatase. ALP hydrolyzes a broad class of phosphate monoesters and
425 functions as transphosphorylase in an alkaline environment [98]. ALP in echinoderms is suggested
426 to play pivotal roles in multiple biological processes, including cell division and differentiation
427 associated with wound healing, mineralization, initiation of regeneration processes, and immune
428 response [99,100]. Thus, ALP in sandfish may influence growth through its involvement in immunity
429 and morphological development. Interestingly, starvation in *A. japonicus* during periods of
430 inactivation elicits a decrease in ALP levels in the body wall and coelomic fluid of the sea
431 cucumber [101], suggesting that ALP activity is also influenced by diet.

432

433 **3.3.2.3. DEUs associated with Retinol metabolism and Phagosome**

434 Retinol metabolism (spu00830) is another KEGG pathway enriched in all hatchery
435 datasets, which is only represented by putative dehydrogenase/reductase SDR family member 4
436 (*DHRS4*). DHRS4 is a carbonyl reducing enzyme that participates in the metabolism of

437 endogenous signal molecules, such as retinoic acid [102], and in the defense against oxidative stress
438 through detoxification of endogenous lipid-derived aldehydes [103]. *TSP1* and Actin were enriched
439 in the pathway "Phagosome" (spu04145). *TSP1* exhibited lower expression in SHO compared to
440 STU, which suggests minimal activation of TSP1-mediated pathways, including phagocytosis, in
441 faster-growing sandfish. Actin was upregulated in SHO group of AAC and PAC and may play a
442 role in the regulation of processes that affect growth, including cytokinesis, cell migration, and
443 cell growth [104,105].
444
445 **3.4. Other genes potentially associated with growth variation**
446 There were other key DEUs that were not associated with any of the significantly enriched
447 GO and KEGG pathways but may play a role in growth variation in juvenile sandfish.
448
449 **3.4.1. DEUs associated with purine metabolism**
450 Genes involved in purine metabolism were differentially expressed. Xanthine
451 dehydrogenase/oxidase (*XDH/XOD*) was represented by two different but highly related (aa
452 similarity: 59.5%) key DEUs. *XDH/XOD* catalyzes the terminal step of purine metabolism,
453 converting purine metabolite hypoxanthine to xanthine and subsequently to uric acid [106]. In
454 addition, we found a DEU in AAC and PAC that is homologous with 5'-nucleotidase (*5NTD*), an
455 enzyme catalyzing the initial step of purine nucleotide degradation (hydrolysis of monophosphate
456 to nucleoside) [107]. Both *XDH/XOD* and *5NTD* were downregulated in SHO, suggesting that purine
457 catabolism may be suppressed in SHO, consequently promoting biosynthesis of purines-related
458 molecules, such as energy-yielding metabolites to support growth.
459

460 **3.4.2. DEUs associated with metabolites and solute transport**

461 The DE analysis also detected four key DEUs involved in cellular solute movement. One
462 of these transporter genes is nose resistant to fluoxetine protein 6-like (*Nrf6*), a transmembrane
463 protein involved in the transport or modification of xenobiotic compounds or particular lipids [108].
464 In addition, three members of solute carrier family were identified, namely, sodium-coupled
465 monocarboxylate transporter 1 (*SLC5A8*), solute carrier family 28 member 3 (*SLC28A3*), and
466 solute carrier family 22 member 15 (*SLC22A5*). *SLC5A8* encodes for a Na^+/glucose co-transporter
467 that facilitates in the transport of monocarboxylates, including short-chain FAs and nicotinate
468 [109,110], *SLC28A3* encodes for pyrimidine and purine nucleosides transporter [111], and *SLC22A5*
469 encodes for an organic cation transporter and carnitine symporter [112] to facilitate carnitine-
470 mediated transport of long-chain FAs from the cytosol to mitochondria for subsequent beta-
471 oxidation and energy production [113]. We also detected the solute transporter genes *SLC23A1*,
472 *SLC26A10*, and organic cation transporter-like (*Orct*) in two hatchery datasets. *SLC23A1*,
473 *SLC26A10*, and *Orct* were upregulated in SHO, suggesting a higher influx of their target molecules
474 (e.g. carnitine, nucleosides, FAs, and cations) to their respective sites of metabolism to induce
475 cellular activities, such as signaling activation, metabolite biosynthesis, and xenobiotic
476 metabolism, consequently influencing the growth of juvenile sea cucumber.

477

478 **3.4.3. DEUs associated with fatty acid metabolism**

479 The DEU analysis identified three key unigenes that encode for enoyl-CoA delta isomerase
480 1, cytochrome P450 4V2, and FA binding protein 3. These genes are involved in the mitochondrial
481 fatty acid (FA) beta-oxidation, which plays a pivotal role in energy derivation through degradation
482 of FAs [114,115]. Upregulation of these unigenes suggests that SHO individuals have higher FA

483 metabolism and mobilization compared to STU, possibly for activating FA-mediated cell signaling
484 pathways or energy production directed for growth.
485
486 **3.4.4. Death domain-containing protein, branched-chain amino acid aminotransferase-like,**
487 **and proline-rich transmembrane protein 1**
488 Unigenes identical to death domain-containing protein 1 (*DTHD1*), branched-chain amino
489 acid aminotransferase-like (*BCAT*), and proline-rich transmembrane protein 1 (*PRRT1*) were also
490 identified as key DEUs. Information on *DTHD1* function is lacking [116]; however, it has been
491 suggested to be involved in activation of apoptosis and inflammatory signaling transduction, which
492 is consistent with the known functions of proteins in the death domain superfamily [117]. *BCAT* is
493 involved in the catabolism of branched-chain amino acids (e.g. leucine, isoleucine, and valine),
494 generating alpha-ketoacids and glutamate in the process [118]. Glutamate is a precursor molecule for
495 the biosynthesis of various biomolecules including amino acids (proline and arginine),
496 neurotransmitters (e.g. gamma-aminobutyrate), and glutathione [119], while alpha-ketoacids may be
497 further catabolized by other enzymes to final products (e.g. acetyl-CoA) that are consumed in
498 tricarboxylic acid (TCA) cycle to promote fatty acid oxidation and energy production [120].
499 Therefore, BCAT may play a role in growth and development through regulation of branched-
500 chain amino acids, glutamate, and alpha-ketoacids-mediated FA metabolism. *PRRT1* has been
501 shown to influence synapse development and function by regulating AMPA receptors in the brain
502 [121]. It is possible that PRRT1 also participates in the development of nervous system in sandfish.
503

504 **3.5. *In silico* microsatellite and SNP markers discovery**

505 Variant discovery was performed on the *H. scabra de novo* transcriptome to mine potential
506 microsatellite and SNP markers. A total of 47,127 microsatellites, distributed across 35,914
507 unigenes, were recovered from the final assembly (Table 4 and Additional File 1 Table S10). Of
508 these, 8,422 unigenes contained more than one microsatellite. Mononucleotide motif dominated
509 the microsatellite types accounting for 86.6% of the total repeat motifs, followed by dinucleotide
510 constituting 8.2%.

511 The KisSplice pipeline discovered 373,196 SNPs, which were distributed to 52,729
512 unigenes. Of these, 86.2% were not in coding sequence (non-CDS), while SNPs detected in coding
513 region (16.7%) comprised 37,191 synonymous and 25,189 non-synonymous types (Table 5).
514 There were more transitions (60.6%) compared to transversions (39.4%) among the final SNP sets.
515 SNP markers developed from the transcriptome have added value because they can be used to
516 study selection and local adaptation to different environmental conditions at spatial and temporal
517 scales [122]. Therefore, the gene-associated SNPs derived from *H. scabra* transcriptome may be
518 valuable in population genomics studies, especially when loci under selection (non-neutral) that
519 have a direct functional impact are of interest.

520 KissDE identified 10,959 potentially growth category-associated SNP (p-adjusted cut-off
521 of < 0.01) (Additional File 1 Table S11). Further filtering growth category-associated SNPs with
522 |Deltaf/DeltaPSI| ≥ 0.5 as threshold reduced the number to only 91 SNPs with high potential of
523 being specific to a growth category. The absolute value of Deltaf/DeltaPSI, a KissDE statistic
524 based on allele frequency differences between two conditions, ranges from 0 to 1, in which a SNP
525 with a value of 1 suggests the SNP has a high probability of being condition specific and could
526 present as a fixed allele for a particular condition [55]. A separate investigation will be necessary to

527 genotype these SNPs and evaluate their utility to differentiate SHO and STU, particularly in view
528 of the pooled sequencing strategy used here which may affect the accuracy of allele frequency
529 estimates used in KissDE. Nonetheless, these putative SNPs represent potential molecular markers
530 to enable marker-assisted selection programs for enhanced growth rates in sandfish.
531

532 **3.6. Comparison with previous studies investigating growth variation in sea cucumbers**

533 Previous transcriptome analysis of growth variation in sea cucumbers have been limited to
534 *A. japonicus*. Downregulation of immune-related genes in slow-growing individuals was
535 associated with global hypometabolism [123,124], a physiological state similar to hibernation to cope
536 with stress due to unfavorable conditions. Similarly, a recent transcriptome study on growth of two
537 populations of *A. japonicus* and their hybrid has also highlighted the overexpression of defense-
538 and immune-related genes, such as heat shock protein (HSPs) genes, in slow-growing individuals
539 [26]. In contrast, our results reveal immune response activation in the fast-growing group based on
540 higher population-wide expression of DEUs possibly encoding for immunity and defense-related
541 genes. Contrasting gene expression patterns between *A. japonicus* and *H. scabra* were also
542 observed for several genes involved in different metabolic processes, including serine protease,
543 *PCSK9*, and IgGFc-binding protein. Further, several key genes reported to be directly associated
544 with growth and development in *A. japonicus* were not detected in *H. scabra*, such as ribosomal
545 proteins (RPLs) and growth factors. While differences in expression patterns of some genes were
546 observed, we also found similar genes with concordant expression in fast-growing individuals for
547 both species, such as fibropellin, *ECI1*, *SLC28A3*, *Orct*, and *DHRS4*.

548 With the work presented here, genes implicated in immune response, solute transport, and
549 energy metabolism are likely involved in growth variation observed in early juvenile *H. scabra* as

evidenced by the concordant patterns of expression (key DEUs) observed across three different hatchery populations. Contrasting results for *A. japonicus* and *H. scabra* indicate that genomic mechanisms underlying growth regulation are complex and varies among different sea cucumber species. Consequently, it is imperative to determine the detailed roles of the differentially expressed genes identified in both species to gain further insights on growth variation in sea cucumbers.

4. Conclusions

This research presented a *de novo* assembly of the early-stage juvenile *H. scabra* transcriptome and identified genes that are potentially associated with growth variation in juvenile sandfish. DEUs between fast- and slow-growing juvenile sandfish across three hatchery populations were related to potentially key molecular pathways and biological processes controlling growth variation, which include carbohydrate binding, ECM organization, fatty-acid metabolism, and metabolite and solute transport. DEUs related to immunity and defense and energy metabolism were upregulated in fast-growing juvenile sandfish, suggesting that they possess a more robust pathogen-defense response and a higher energy output to sustain increased growth rate. Our results also revealed a large number of potential microsatellites and growth category-associated SNP markers. Functional studies on these genes and SNPs are required to elucidate their roles in growth regulation in sea cucumbers. Overall, our findings improve the current understanding on the genetic basis of growth variation in sea cucumbers and represents an invaluable genomic resource to facilitate future functional genomics-based research and applications in sandfish and other sea cucumbers, including selecting for genes associated with faster-growing phenotypes for marker-assisted selection and broodstock enhancement.

5. Availability of data and materials

All raw Illumina data were submitted to NCBI Short Read Archive (SRA) Sequence Database (Bio-Project: PRJNA433757); Accession Numbers: SRR6714451 – SRR6714458 and SRR8713066 - SRR8713073). The final assembly used in all subsequent analyses is available in NCBI's Transcriptome Shotgun Assembly database under the TSA accession GIRH01000000. Additional File 3 contains the annotation result of Trinotate and diamondblast.

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7. Author's contribution

JFFO: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – Original Draft, Writing – Review & Editing, Project administration; **GGG**: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – Original Draft, Writing – Review & Editing, Project administration; **RRG**: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – Review & Editing, Project administration;

8. Conflicts of interest

The authors declare no conflict of interest.

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916
917

918 # Tables

919

920 **Table 1.** Sequencing and assembly statistics of juvenile *H. scabra* transcriptome.

Description	Statistics
Number of raw reads used	298,348,055
Total assembled bases (bp)	148,677,120
Number of sequences	154,657
Number of clusters (unigenes)	147,981
% GC	38.2
N50 (bp)	1,572
ExN50 (bp)	2,559
Average sequence length (bp)	961.1
Length range (bp)	200 - 18,779
Transrate	
Raw score	0.3392
Optimal score	0.3439
BUSCO	
Complete	94.1% (285 ref. genes)
Single-copy	80.9% (245)
Duplicated	13.2% (40)
Fragmented	4.3% (13)
Missing	1.6% (5)
RMBT	89.8% – 97.5%

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923 **Table 2.** Annotation of the juvenile *H. scabra* transcriptome assembly.

	No. of unigenes	Proportion (%)
Unigenes	154,274	100
Annotation tool		
nr	25,058	16.2
SwissProt	17,476	11.3
KEGG	13,173	8.5
KOG	5,625	3.6
GO	17,764	11.5
eggNOG	14,100	9.1
PFAM	15,176	9.8
SignalP	2,415	1.6
tmHMM	5,432	3.5

924

925 **Table 3. Summary of 30 key differentially expressed unigenes (DEUs) between growth**
926 **variants (SHO and STU) of juvenile *H. scabra*.**

927

Unigene ID	Change	Gene Name	E-value	% ID	Accession
Cluster-34569.0	Up	putative cytochrome P450 4V2	$6E^{-76}$	55.8	PIK50795.1
Cluster-64461.0	Up	putative ladderlectin-like	$8E^{-44}$	46.6	PIK61382.1
Cluster-4263.14805	Up	putative histidine ammonia-lyase	0	72.2	PIK45994.1
Cluster-4263.47588	Down	thrombospondin-1-like	0	57.0	XP_022097497.1
Cluster-49506.0	Up	putative sodium-coupled monocarboxylate transporter 1	0	62.2	PIK61033.1
Cluster-4263.47424	Down	putative death domain-containing protein 1	0	75.7	PIK47993.1
Cluster-43224.0	Up	PREDICTED: lactose-binding lectin l-2-like	$8E^{-15}$	35.5	XP_015231948.1
Cluster-4263.37946	Up	mannan-binding C-type lectin	$3E^{-52}$	47.4	ABC87994.1
Cluster-4263.48517	Down	hypothetical protein BSL78_12715	$2E^{-43}$	44.1	PIK50391.1
Cluster-4263.51462	Up	solute carrier family 28 member 3	0	53.8	XP_030843617.1
Cluster-4263.30459	Down	C-type lectin 4	$9E^{-25}$	32.9	PIK46115.1
Cluster-4263.3194	Down	LOW QUALITY PROTEIN: xanthine dehydrogenase	$2E^{-149}$	67.2	XP_025837350.1
Cluster-4263.11672	Up	putative nose resistant to fluoxetine protein 6	0	46.4	PIK55374.1
Cluster-72570.0	Up	putative solute carrier family 22 member 5-like	$2E^{-64}$	54.6	PIK49230.1
Cluster-4263.27907	Up	putative fatty acid-binding protein type 3-like	$2E^{-42}$	53.9	PIK38828.1
Cluster-4263.15443	Up	hypothetical protein BSL78_13655	$5E^{-22}$	24.2	PIK49462.1
Cluster-4263.20106	Up	LOW QUALITY PROTEIN: deleted in malignant brain tumors 1 protein-like	$9E^{-88}$	35.3	XP_029286412.1

Cluster-68382.0	Up	putative proline-rich transmembrane protein 1	$5E^{-12}$	43.8	PIK39817.1
Cluster-55341.0	Down	PREDICTED: enoyl-CoA delta isomerase 1, mitochondrial-like	$1E^{-59}$	37.9	XP_006821323.1
Cluster-63482.0	Up	putative natterin-3-like	$2E^{-71}$	38.9	PIK58441.1
Cluster-10514.0	Down	xanthine dehydrogenase/oxidase -like	0	60.3	XP_033626714.1
Cluster-4263.18390	Up	putative alpha-amylase 4N isoform X2	0	76.5	PIK42765.1
Cluster-66904.0	Up	short-chain collagen C4-like	$7E^{-52}$	45.2	XP_028410684.1
Cluster-4263.45206	Down	hypothetical protein BSL78_07876	0	49.6	PIK55146.1
Cluster-4263.8122	Up	proprotein convertase subtilisin/kexin type 9 preproprotein	$6E^{-70}$	60.5	ABC87995.1
Cluster-4263.5527	Up	short-chain collagen C4-like	$9E^{-55}$	46.1	XP_028410684.1
Cluster-49945.0	Up	putative alkaline phosphatase, tissue-nonspecific isozyme-like	0	72.9	PIK33162.1
Cluster-4263.18396	Up	uncharacterized protein LOC575598	$2E^{-111}$	42.7	XP_030851419.1
Cluster-71465.0	Up	putative branched-chain-amino-acid aminotransferase-like protein 1	$5E^{-28}$	33.5	PIK46296.1
Cluster-4263.31616	Up	Ammasin	$1e^{-79}$	35.7	ABA26923.1

937 **Table 4**. Statistics of microsatellite and SNP identified from juvenile *H. scabra* transcriptome.

Variant type	Classification	Count (%)
Microsatellite	**Total**	**47,127 (100)**
	Mononucleotide	40,819 (86.6)
	Dinucleotide	3,875 (8.2)
	Trinucleotide	1,441 (3.1)
	Tetranucleotide	845 (1.8)
	Pentanucleotide	124 (0.3)
	Hexanucleotide	23 (0.05)
SNP	**Total**	**373,196 (100)**
	Non-CDS	310,678 (86.2)
	In CDS	62,380 (16.7)
	Transitions	226,265 (60.6)
	A/G	114,304 (30.6)
	C/T	111,961 (30)
	Transversions	146,931 (39.4)
	T/A	52,981 (14.2)
	A/C	35,645 (9.5)
	G/T	33,531 (9)
	C/G	24,774 (6.6)

938

11. Figures

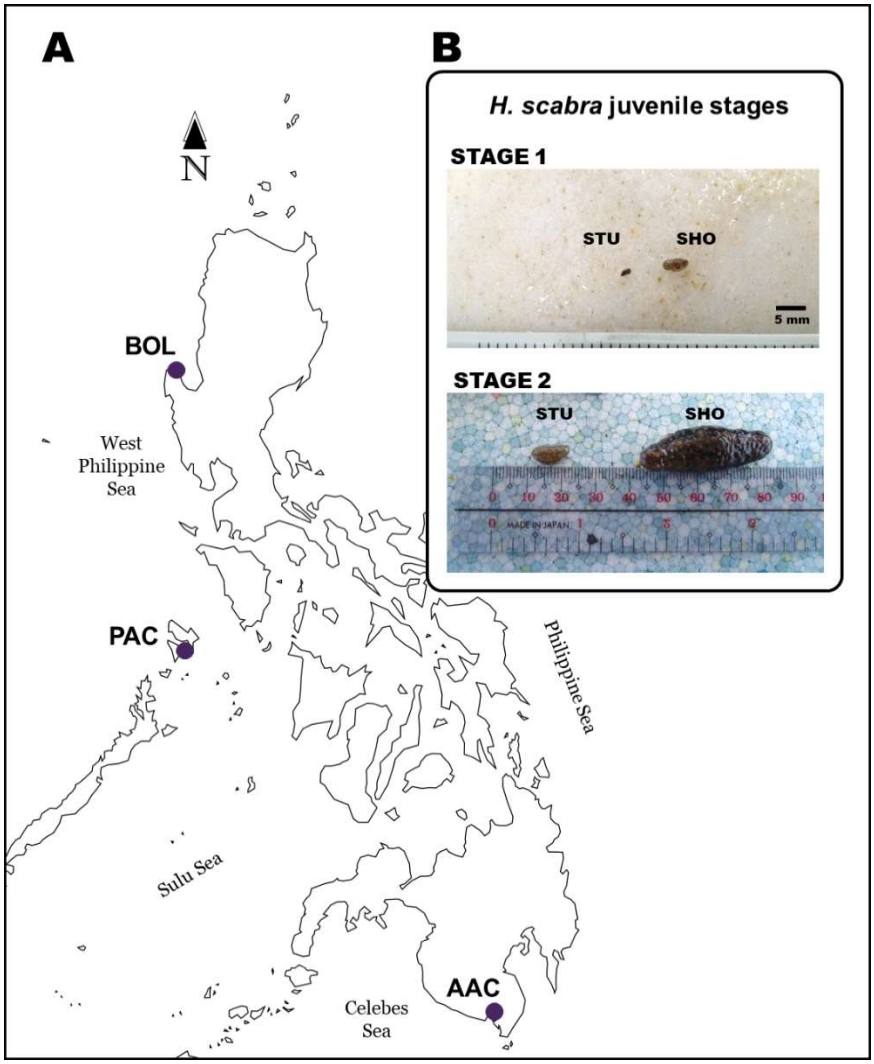

Figure 1. *Holothuria scabra* sample information. (A) The three sandfish hatchery sampling collection sites denoted by purple circles. (B) Sample images of representative individuals from SHO and STU at Stages 1 (45 days post-fertilization) and 2 (75 days post-fertilization).

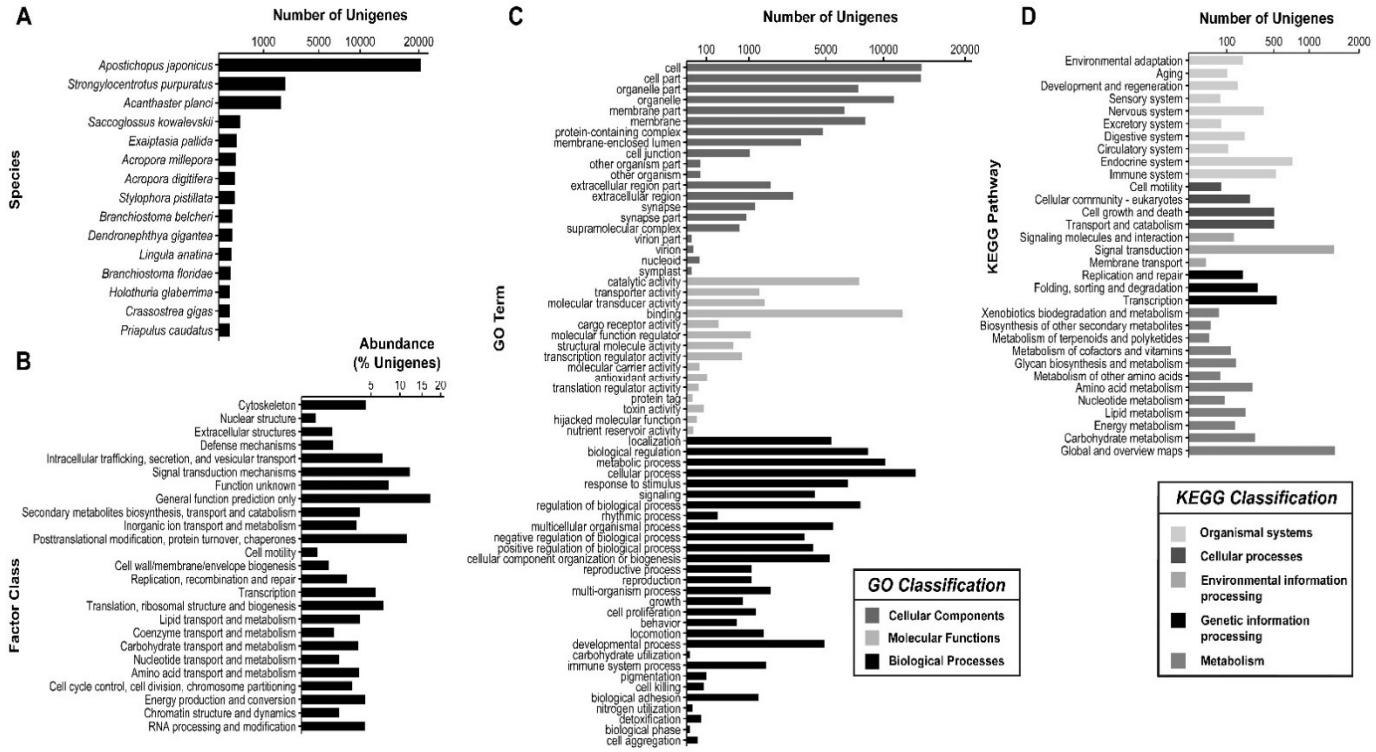

Figure 2. Summary of *H.scabra* transcriptome annotation classified according to top species distribution from nr, eukaryotic ortholog groups (KOG), Gene Ontology (GO), and Kyoto Encyclopedia of Genes and Genomes (KEGG) databases. (A) Top 15 most represented species based on homology search against nr. (B) Frequency distribution of unigenes according to 25 functional categories of KOG. (C) Gene ontology distribution of assembled unigenes for the three general GO classifications. (D) Pathway classification and distribution of unigenes according to five major KEGG categories.

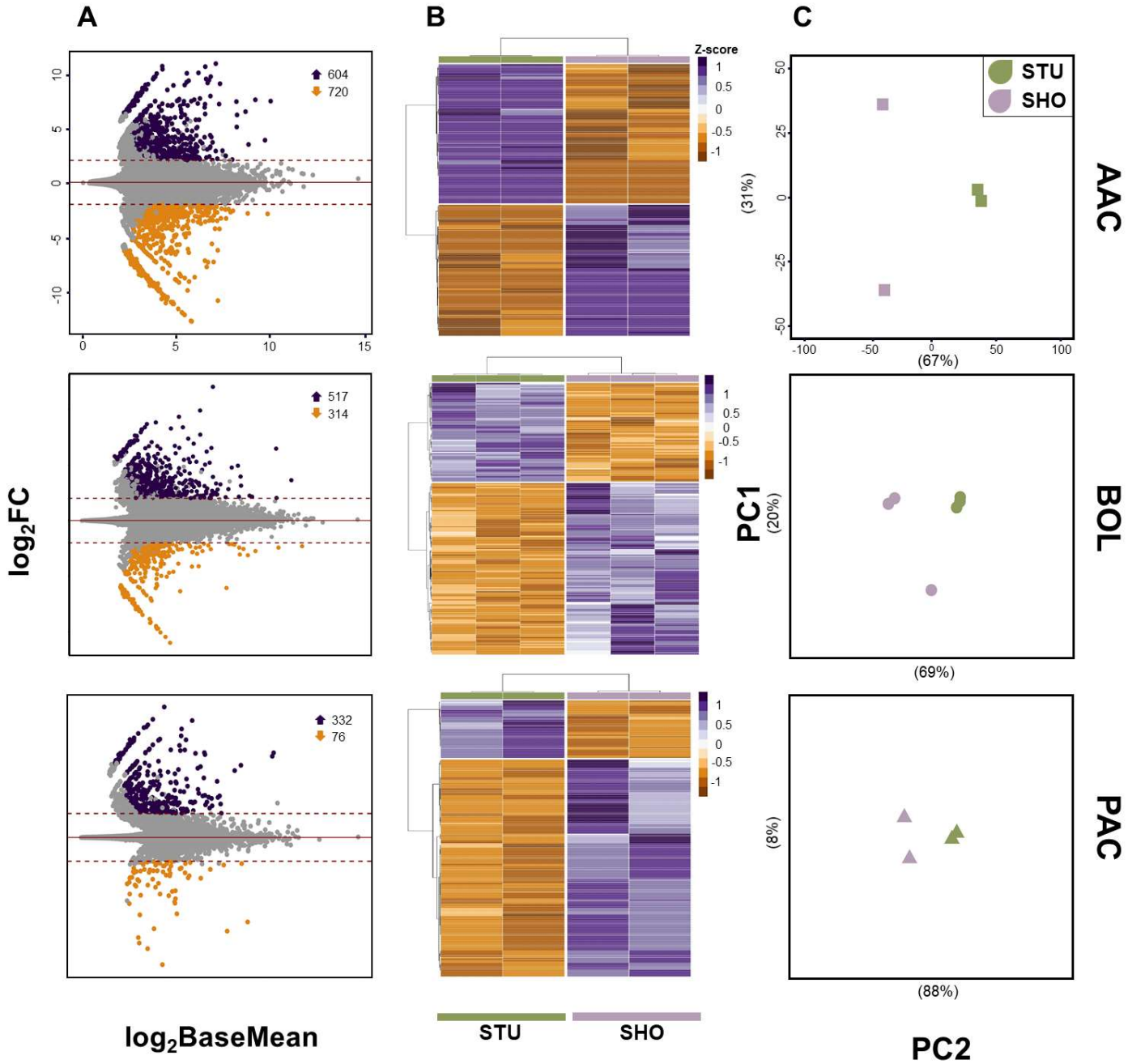

Figure 3. Different representations of gene expression analyses between SHO and STU categories of *H. scabra* for hatchery populations AAC, BOL, and PAC. (A) MA plots highlighting the significant unigenes (FDR $p < 0.01$) with expression levels of $|\log2FC| > 2$ (denoted by dashed lines). Dots in purple and orange denote upregulated and downregulated unigenes, respectively. Number of upregulated and downregulated unigenes in each hatchery dataset are denoted by up and down arrow, respectively. (B) and (C) are growth-

957 category clustering profiles based on rlog-transformed unigene expression. (B) Heatmaps showing the
958 clustering of SHO and STU samples per dataset. For representation purposes, only the top 200 significant
959 DEUs (log2FC| > 2, FDR < 0.01) were shown. (C) Clustering of the global gene expression in three
960 populations using principal components analysis (PCA).